Market Introduction of Hydrogen Fuel

vorgelegt von

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zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften

- Dr. Ing. -

genehmigte Dissertation

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Tag der wissenschaftlichen Aussprache: 24. März 2015

Berlin 2016

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2/4/6DS	2/4/6 Degrees Scenario of the IEA
ACEA	Association des Constructeurs Européens d'Automobiles- European Automobile Manufacturers Association
ADAC	Allgemeiner Deutscher Automobilclub
AFCC	Automotive Fuel Cell Cooperation
AOP I / II	Auto-Oil-Programme, part I / II
b / bbl	barrel
BM	Bundesministerium
boe	Barrel of oil equivalent
BTL	Biomass-to-Liquid
CAFE	Corporate Average Fuel Economy
CARB	Californian Air Resources Board
CEN	Committee of European Normalisation
CH_2	Compressed hydrogen
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_{2equiv}	CO_2-equivalent
CONCAWE	Conservation of Clean Air and Water in Europe
COP	Conference of the Parties to the UNFCCC
CRF	Centro Ricerche Fiat
CTL	Coal-to-Liquids
dbb	DBB Fuel Cell Engines GmbH
DESA	Department of Economic and Social Affairs of the UN Secretariat
DG	Directorate General
DG TREN	Directorate-General Transport and Energy
DI	Direct Injection
DICI	Direct Injection Compression Ignition
DIN	Deutsches Institut für Normung
DISI	Direct Injection Spark Ignition
DME	Dimethyl Ether
DOD	Depth of Discharge
DOE	United States Department of Energy
DPF	Diesel particulate filter
EC	European Commission
ECCP	European Climate Change Programme
EEA	European Environment Agency
EEC	European Economic Community
EERE	US Department of Energy's Office of Energy Efficiency and Renewable Energy
EEV	Enhanced environmentally friendly vehicle
ENGVA	European Natural Gas Vehicle Association
EPO	European Patent Office
ETBE	Ethyl-tertiary-butyl-ether
ETS	Emissions Trading Scheme
EU	European Union
EU10	Accession countries to the European Union on 1 May 2004. The EU10 comprises the following ten countries: Estonia, Latvia, Lithuania, Poland, Slovenia, Slovak Republic, Czech Republic, Hungary, Malta and Cyprus
EU15	Member countries in the European Union prior to the accession of ten candidate countries on 1 May 2004. The EU15 comprised the following fifteen countries: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom.
EU25	Comprises the countries of EU10 and EU15
EU27	Comprises the countries of EU25 plus Bulgaria and Romania
EUAs	Emission Allowances
EUCAR	European Council for Automotive R&D
FAME	Fatty Acid Methyl Ester (biodiesel)
FC	Fuel Cell
FC(E)(H)V	Fuel Cell (Electric) (Hybrid) Vehicle
FP5 / 6	Fifth / Sixth Framework Programme
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIC	Gross Inland Consumption
GTL	Gas-to-Liquids
HDV	Heavy-duty vehicle
HEV	Hybrid electric vehicle
H_2FC	Hydrogen and Fuel Cells
HGV	Hydrogen Gas Vehicle
HLG	High Level Group on Hydrogen and Fuel Cells
IANGV	International Association for Natural Gas Vehicles
ICE	Internal Combustion Engine
IEA	International Energy Agency
IEKP	Integriertes Energie- und Klimaprogramm (Integrated Energy and Climate Protection Programme)
IPC	International Patent Classification
IPCC	Intergovernmental Panel on Climate Change

ISO	International Standards Organisation
JI	Joint implementation
k-km	kilo kilometres
kg	Kilogram
ktoe	tonnes of oil equivalent
kW	kilowatt
LH_2	Liquid hydrogen
LPG	Liquefied Petroleum Gas
MEA	Membrane-electrode-assembly
MKS	Mobilitäts- und Kraftstoffstrategie
MTBE	Methyl-tertio-butyl-ether
Mtoe	Million tons of oil equivalent
NAP	National Allocation Plan
NECD	National Emission Ceilings Directive
NEDC	New European Driving Cycle
NGO	Non-governmental organisation
NGV	Natural Gas Vehicle
NHTSA	Department of Transportation's National Highway Traffic Safety Administration
NIP	Nationales Innovationsprogramm Wasserstoff und Brennstoffzelle
NMHC	Non methane hydrocarbon
NO_x	Nitrogen oxide
NREL	National Renewable Energy Laboratory
NYMEX	New York Mercantile Exchange
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
OPEC	Organization of Petroleum Exporting Countries
ORR	Oxygen Reduction Reaction
p.a.	per annum
PAH	Polycyclic aromatic hydrocarbons
PE	Polyethylene
PI	Positive (spark) Ignition
pkm	Passenger km
PISI	Port injection spark ignition
PM	Particulate matter
ppb / ppm	parts per billion / million
PPP	Purchasing Power Parity
PRD	Pressure Relief Device
QVM	Qualified vehicle modifier
R&D	Research and Development
R&DD	Research, Development and Demonstration
RES	Renewable Energy Sources
RTD	Research and Technological Development
SAE	Society of Automobile Engineers
SME	Small and medium enterprises
SO_2	Sulphur dioxide
SUV	Sport Utility Vehicle
T&E	European Federation for Transport and Environment (Green NGO)
tkm	Ton-km
TtW	Tank-to-Wheel
UDC	Urban driving cycles
UITP	International Association of Public Transport
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UPS	Uninterrupted power supply
VDA	Verein Deutscher Automobilhersteller (Association of German Automobile Industry)
VDI	Verein Deutscher Ingenieure
VOC	Volatile Organic Compounds
w/o	without
WMO	World Meteorological Organization
WTI	West Texas Intermediate
WtT	Well-to-Tank
WtW	Well-to-Wheels
ZEV	Zero Emission Vehicles

1 Introduction

1.1 Background

Hydrogen fuel interlinked with Fuel Cell Vehicle (FCV) technology is currently re-entering the stage as the energy vector of the future. The idea of integrating clean hydrogen fuel into a sustainable hydrogen economy is no longer the preserve of a limited number of ingenious scientists or of enthusiasts. In recent years all big car manufacturers and most mineral oil companies, the governments of the leading industrialised countries as well as the related main supra-governmental organisations have established serious research and deployment strategies targeted to the promotion of hydrogen as an energy carrier, in particular as a motor fuel.

After years of announcements, empty promises and waiting games, but still continued research and development work, hydrogen and fuel cell (H_2FC)-technologies have reached a technological level which allows market introduction. Stakeholders of the H_2FC-technology gathered in associations and bilateral agreements and identified jointly key markets. In addition, they sought support from the governments to prepare the market entry of the technology. Germany was identified as one of the key markets and will therefore be used as a case study within this work at hand.

Fuel cell vehicles (FCVs) and an H_2-infrastructure have to be introduced to the market in parallel. The financial and other efforts for a market penetration just for one of these two technologies would be huge, but their market success is indispensably intertwined. Market success requires well-timed concerted actions between all stakeholders. The task is tremendous; coordination and cooperation effort as well as investments still to be made will be very high, but the reward is the chance to overcome some of the most pressing problems of our civilization:

- The **reliable access to energy at low-cost** is an essential success factor for any national economy. The finite nature of fossil fuels within the foreseeable future, partly even within the life span of the generation currently in active life, ultimately threatens the long-term prosperity of developed countries and hinders the growth in emerging economies. The need for a transition in the world's energy infrastructure is all the more urgent as energy demand could double or triple as the population rises and developing countries expand their economies to overcome poverty by 2050. [WBCSD, 2004, p. 3] In the meantime, increasingly difficult access to fossil fuel resources is forcing European countries to compromise politically with unstable, non-democratic regimes outside the EU, where the bulk of the remaining resources of oil and gas lies. Furthermore, increasing energy costs are embarrassing to the prosperous classes of the society as the phenomena of "fuel poverty" grows.
- **Ensuring sustainable mobility** despite the constant growth of individual transport. Europeans enjoy unprecedented levels of personal mobility. The EU stimulated this personal mobility as well as the freedom of goods movement by opening national markets and by removing legal, physical and technical obstacles. However, today's transport patterns and growth rates are unsustainable. Nevertheless, the transport sector generates 10% of EU wealth in terms of gross domestic product and provides more than ten million jobs. In any case, liberalisation alone cannot provide sustainability. The transport sector is responsible for around a quarter of EU CO_2-emissions. [http://ec.europa.eu/clima/policies/-transport/index_en.htm, 08.05.2015] If the climate targets are still in range, then the right incentives have to be set now to promote sustainable transport options.

- The first **consequences of climate change** - predicted already for over twenty years, but only more recently becoming noticeable - make themselves felt and force policy makers and societies to react. At best, experts estimate it could be possible to stabilise the atmospheric CO_2-concentration at a maximum of 450 ppm in the long-term, which should confine the global temperature increase to 2°C. A 450 ppm trajectory is an ambitious undertaking in a further developing world. It requires a wide range of technologies with high investment and complex choices, completely transforming energy production and use. [IEA, 2009 (1), p. 46] Renewable energies have the potential to soften the consequences of climate change. The effect would be the achievement of a significant reduction in atmospheric CO_2-concentration, the earlier the better. However, most technologies have not yet been maturely, *see footnote 159*, developed. In addition, due to the intermittent nature of most of the renewable energy sources an energy storage system is needed to match energy availability and demand. Hydrogen could serve as such an energy storage system, furthermore allowing the transport of energy from remote areas, insufficiently connected to the national grid, to the place of demand.
- Regardless of any successful efforts by the car industry to improve energy efficiency and air pollution control technology, the steady increase in individual transport leads to an **increase in transport related energy consumption**. Despite large progress in vehicle exhaust cleaning technologies, transport related **air pollution** still results in several hundreds of thousands of premature deaths, increased health costs and millions of lost working days in Europe each year. Transport is the main source of $PM_{2.5}$, the pollutant that is of most concern for human health. Recent studies show that current policies will not be able to achieve the targets of the European Commission aiming at levels of air quality that do not give rise to significant negative impacts on and risks to human health and the environment, see section 3.1.

Sustainably produced hydrogen sounds like a logical solution to all problems mentioned: eliminating greenhouse gas emissions, removing the problem of local and transboundary air pollution, providing a secure indigenous energy carrier that is more evenly distributed among all regions and countries of the world, promoting local value creation from the use of alternative energy resources and strengthening European industry. In combination with fuel cell technology it even promises a significant increase in energy efficiency, technology innovation and, therefore, an increased or at least sustained competitiveness of European industry. Furthermore, the development of new technologies as well as the exploitation of more and, particularly, locally labour intensive renewable energies have the potential to increase the quantity and quality of employment in Europe.

The expectations in H_2FC-technologies are high. Nations, global and local industries as well as research organisations are competing for a good starting position towards the hydrogen economy. The industry and governments put on heavy research and deployment programmes which result in thousands of patent applications annually. In addition, they are organising networks to enhance co-operation and communication between the main actors. The progress in technology development and forecasts for market penetration are ambitious.

1.2 Main aim of the thesis

The main aim of this work is to provide arguments for a realistic assessment of the role of hydrogen for the energy supply of future road transport. The work concentrates on the market introduction of hydrogen fuel for cars. Light and heavy duty vehicles are currently not developed seriously for any mid-term use of hydrogen fuel. The work shall deduce the market potential of hydrogen fuel based on the analysis of the past, current and future market environment. Any results shall be based on a detailed description and evaluation of the stakeholders as well as the driving and inhibiting factors for the market introduction of hydrogen fuel.

In more specific terms, the thesis is targeted at describing conditions for the market entry of hydrogen fuel in Germany for the prognosis horizons of 2020, 2030 and 2050. Facts shall be developed on the grounds of compelling framework conditions and user acceptance assumptions, rather than based on political ideas, media hype or messages spread by the marketing departments of the car industry which push a new technology every other year. Assumptions shall be verified by conditions set by the institutional framework, a literature and patent analysis. Finally, they shall be discussed with experts in a Delphi analysis and are summarised using an adapted version of Porter's Model of Five Competitive Forces.

Realistic market penetration information is urgently required by all parties investing in H_2FC- and related technologies as well as city-planners etc. However, data available is heavily influenced by interest groups, often lacking a realistic foundation and frequently ignores the wishes of the customer and is therefore often unreliable.

1.3 Structure of the thesis

The work is structured into seven parts. The first section is, naturally, this introduction. Section two on **"Energy consumption and environmental impact of transport"** describes the role of transport in the energy sector, the transport volumes in the EU, the environmental impact of transport, the external costs of transport as well as the current vehicle market.

The third section on **"Market framework conditions"** explains which political, legal and economic factors have the potential to drive or inhibit the market introduction of hydrogen fuel.

The fourth section on the **"Research, development and deployment perspective"** gives an overview of the main hydrogen projects showing the developments of the past and the market targets and strategies for the future. The current state of the art and the potential of H_2FC-technology is assessed. In addition, an overview of competing vehicle technologies and fuels is given.

Section five deals with the "**Market transformation perspective"**. A stakeholder analysis summarises the interests of the main stakeholders, including public acceptance of the technology. It also dissects the behaviour and roles of the various market actors, how their attitudes guide decisions and how these attitudes are influenced. It localises the position of H_2FCV-technology in the product life-cycle. Furthermore, the role of technology learning for the achievement of economy of scales and cost reduction of the technology is analysed. It focuses on the market barriers and driving factors influencing the widespread market penetration of H_2FCV-technology in the transport sector, with emphasis both on investors and consumers.[1]

The sixth section **"Market development perspectives of hydrogen fuel"** is targeted at analysing the pathway to market entry and market growth using different analytical instruments:

- Literature analysis: Analysis of the status quo of the H_2FCV-technology market as well as evaluation of statements of manufacturers on market introduction plans.
- Patent Analysis of H_2FCV-technology.

[1] The definitions are adapted from IEA/OECD, 2003

- Delphi-Analysis to assess the circumstances of H_2FCV-technology market development as well as competing technologies.
- Adaptation of the Porter Model of Five Competitive Forces to analyse competition in the H_2FCV-industry, to evaluate the potential of new competitors as well as substitutes, customer power and suppliers power. The Porter Model is used to value all available results.

Finally, all results are summarised in section seven in one possible **technology deployment pathway** describing the necessary (societal) framework conditions for the H_2FCV-technology market penetration process.

2 Energy consumption and environmental impact of transport

2.1 Global and European energy consumption

Today, the main energy consumers are located in the industrialised countries. In 2013, OECD (Organisation for Economic Co-operation and Development) countries[2] added 44% to the world primary energy consumption of 12.73 Gtoe (see *Figure 2-1*), China 22.4%, India 4.7% and other Asia 13.4%. [BP, 2014, sheet: Primary Energy - Consumption by fuel].

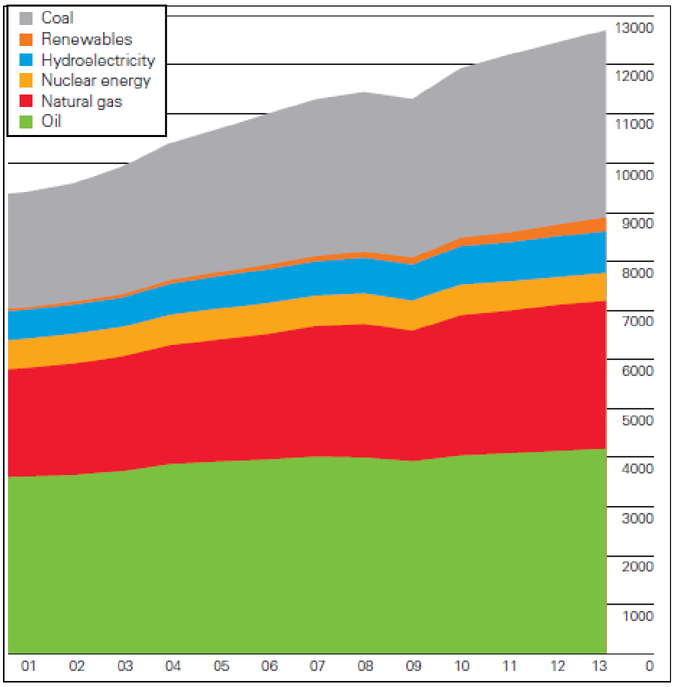

Figure 2-1: Primary energy consumption in Gtoe [BP, 2014, p. 42]

Several organisations perform regular energy forecasts. In the following, three different scenarios are used to describe future energy consumption and Green-house Gas (GHG) emission patterns.

During recent years the EU has managed to implement a coherent set of statistics to monitor policy impacts on energy demand and GHG-emissions. This is a cornerstone for successful energy and environmental management. The **EU Reference Scenario of 2013 (RS_{2013})** describes the EU energy system, taking into account population and economic developments, energy efficiency gains, market penetration of new technologies and renewables as well as changes in the energy mix driven by relative prices, costs and regulation. The **IEA Reference and "450-ppm"-Scenarios** depict global energy consumption patterns which will influence energy security, availability and price of fuels in Europe. They illustrate how changes in global and European energy consumption patterns could contribute to climate change. With its **Statistical Review of World Energy BP** has provided globally consistent data on world energy markets for 63 years taking into consideration changes in policy, technology and the economy. The most recent version extends up to 2035 and was published in January 2014. This work refers to the 2013 version which goes up to the year 2030, due to reasons of comparability with IEA and EU data.

The regional picture of energy demand will change significantly by 2030 as 93% (IEA Reference Scenario) or 96% (BP Scenario) of the prospective energy demand increase is accounted for by non-OECD countries. By 2030 OECD countries will account for 35% of world consumption. The largest growth is achieved in Asia, in particular in China, which showed an average increase in energy consumption of 9.5% between 2001 and 2010. China and India alone will represent over 53% of the incremental demand from 2007 to 2030 (see *Figure 2-2*). [BP, 2012, p.9, 11, 45; IEA, 2009 (2), p. 1; IEA/OECD, Paris, 2009, p. 21, 37]

[2] Australia, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, The Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom and the United States

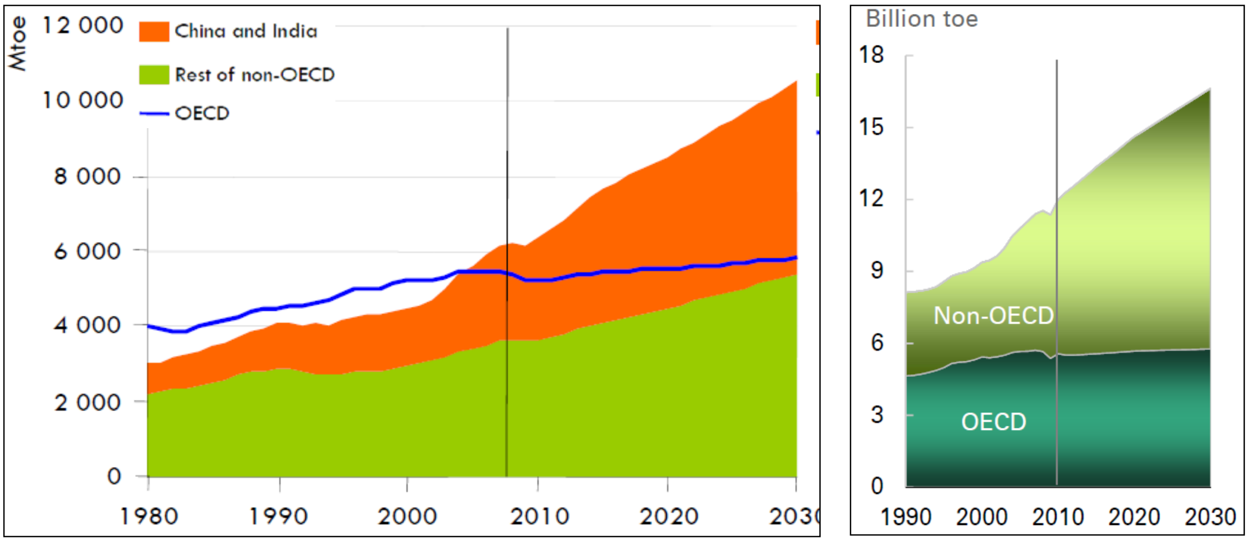

Figure 2-2: World primary energy demand, IEA Reference (left) and BP-Scenario (right) [IEA, 2009 (1), p. 3; BP, 2012, p. 10]

The **IEA 2009 Reference Scenario** sees world primary energy supply as 40% higher in 2030 than in 2007, assuming no change in government policies occurs. This would cause a global temperature rise of up to 6°C (6 Degrees Scenario (6DS)). The IEA also set out an energy pathway consistent with a 50% chance of limiting the increase in the average global temperature to 2°C, avoiding the most severe weather extremes and sea-level rise. This would need to stabilise the atmospheric GHG-concentration at 450 ppm CO_{2equiv}[3] implying a world energy demand increase of “only” 19%. [IEA, 2009 (1), p. 46; BP, 2012, p. 11]

According to IEA, world energy resources are adequate to meet the projected demand increase for the various fuels through to 2030 and well beyond. However, the Reference Scenario shows profound implications for the environment and the climate as well as energy security and economic development. To realise the 450-ppm-Scenario, additional investments of 10,500 GUSD are needed globally in the energy sector in the period 2010-2030, relative to the Reference Scenario, but investments in industry, transport and buildings would be more than offset by fuel cost savings, which in the transport sector alone would amount to over 6,200 GUSD over the period. The 450-ppm-Scenario also offers important energy security, air pollution and environmental cost-benefits. [IEA, 2009 (2), p. 4-6]

The **EU Reference Scenario RS$_{2013}$** includes the national or EU policies relevant to the EU energy system implemented until spring 2012. RS$_{2013}$ starts from the assumption that the legally binding GHG- and Renewable Energy Sources (RES) targets as well as the non-binding energy efficiency goals for 2020 will be achieved.[4] The *EU Gross Inland Consumption (GIC)* [5]was projected to decrease slightly by 1% between 2010 and 2030 from to 1,767

3 The equivalent carbon dioxide (CO_{2equiv}) concentration causes the same amount of radiative forcing as a given mixture of carbon dioxide and other GHG.

4 EU Emission Trading System, Regulation 2009/443/EC on CO_2 from cars, Regulation 2007/715/EC on EURO 5 and 6 standards,Fuel Quality Directive 2009/30/EC, Directive 2009/28/EC targeting on 20% of renewables in total and 10% renewable fuels in the transport sector by 2020, Decision 2009/406/EC (GHG-reduction of 20% (30%) by 2020), Regulation 510/2011 on CO_2 from vans, Energy Efficiency Directive 2012/27/EU targeting at 20% efficiency gain between 2014-2020.

5 The ***final energy consumption*** is the total energy consumed by end users, e.g. households, industry and agriculture. It excludes energy which is used by the energy sector itself for deliveries or transformation. It also excludes fuel transformed in the electrical power stations of industrial auto-producers and coke transformed into blast-furnace gas where this is part of the transformation sector.

to 1,754 Mtoe in RS_{2013}, (see *Figure 2-3*). RS_{2013} showed a considerable decoupling of both energy consumption and carbon emissions from Gross Domestic Product (GDP) growth, making the EU27 one of the world's least carbon-intensive economies. In EU27, the carbon intensity declined by 42% between 1990 and 2010 (394 gCO_2/€ of GDP).

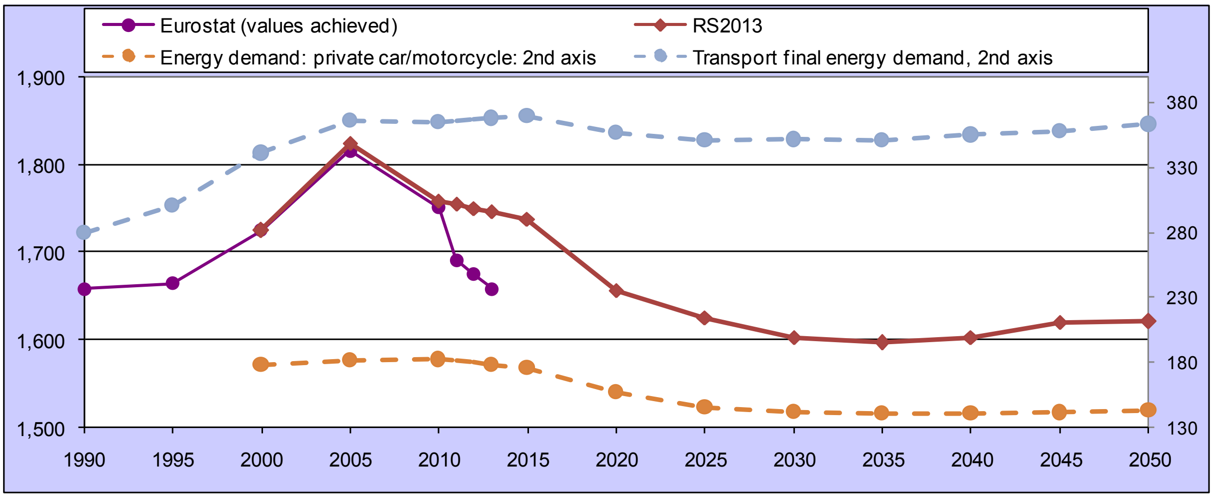

Figure 2-3: Projected Gross Inland Energy Consumption in Mtoe, EU27, 2030, comparison with values achieved [EC, DG Energy et.al., 2013, p. 70-71; Eurostat statistics, 2015]

RS_{2013} is characterised by a restructuring away from fossil fuels. In consequence, import dependency amounts to 55% in RS_{2013} by 2030. By 2020, the RES-target of 20% in final energy consumption could be almost reached (19.9%). [EC, DG Energy et.al., 2013, p. 49, 86et seq.] RS_{2013} shows accelerating energy efficiency improvements. The downward trend on energy consumption commenced before the onset of the economic crisis, with EU energy consumption having peaked in 2006. Despite the gradual economic recovery, total GIC and passenger car/motorcycles energy demand do not resume growth, but are projected to decrease until 2035 and demonstrate a moderate increase thereafter. Thus, by 2035 the impact of the current measures will have phased out, (see *Figure 2-3*).

Today, transport is an essential element of our modern society ensuring people's access to jobs, goods and services, education, leisure and tourism activities. The mobility of persons is an essential right of the citizens in the EU. The global economy is based on the division of labour, naturally causing the transport of raw materials, semi-finished and finished products making freight transport a vital component of the competitiveness of European industry and services. The parameter "car motorisation" is a key indicator characterising the development of a national economy. The EU's sustainable transport policy is aimed to ensure that the various transport systems meet the citizens' economic, social and environmental needs. **Sustainable mobility** is defined as the ability of a society to move freely and communicate comprehensively without having to accept disadvantages. [Shell Deutschland, 2009, p. 6] The decoupling of transport volume growth from the economic (GDP) growth and **"Greening of Transport"**, i.e. the reduction of energy consumption and emissions per person-kilometre

The ***Gross Inland Consumption*** is defined as primary production plus imports, recovered products and stock change, less exports and fuel supply to maritime bunkers (for seagoing ships of all flags). It therefore reflects the energy necessary to satisfy inland consumption within the limits of national territory. [http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy; 14.03.2013] Final energy and GIC differ by 5% in BS2009. The GIC also includes losses in electricity generation and other transformation processes as well as energy use for non-energy purposes, such as chemical feedstock. The gap is an indicator for the transformation efficiency of the EU energy system. The gap becomes smaller due to the replacement of old power stations with more efficient ones.

are main transport policy goals of the EU. Passenger transport volumes are closely linked to income and car ownership and thus, with GDP.[6]

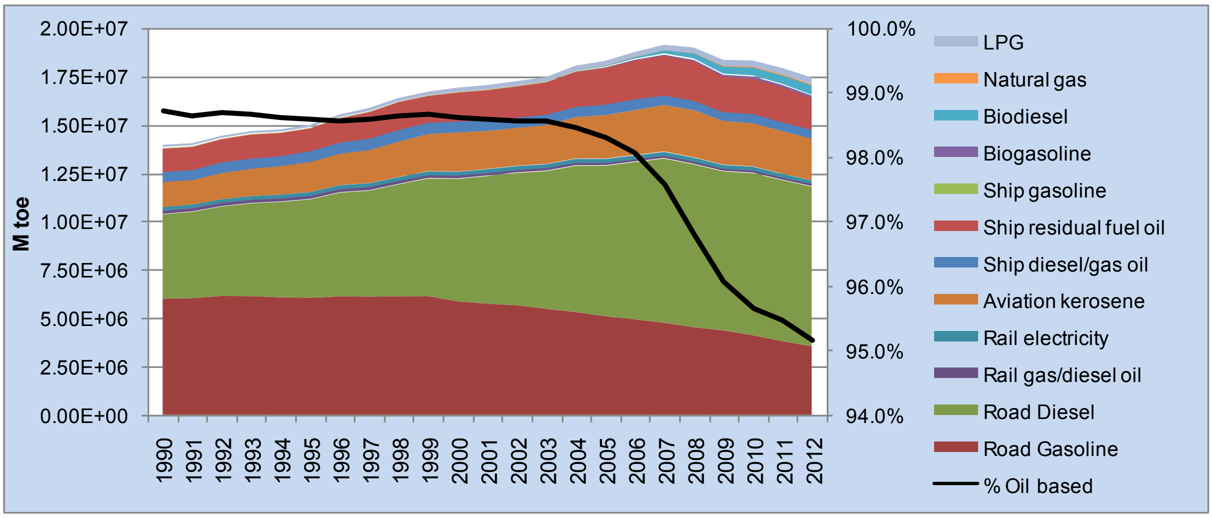

Figure 2-4: Transport energy consumption in EU27 in Mtoe and share of oil based fuels[7]

Road transport needed 73% of total transport energy consumption in 2011, see *Figure 2-4*. According to RS_{2013}, transport energy demand increases by 30% by 2050 compared to 1990, energy demand for passenger cars and motorcycles decreases by 21% compared to 2005 (most recent data available).

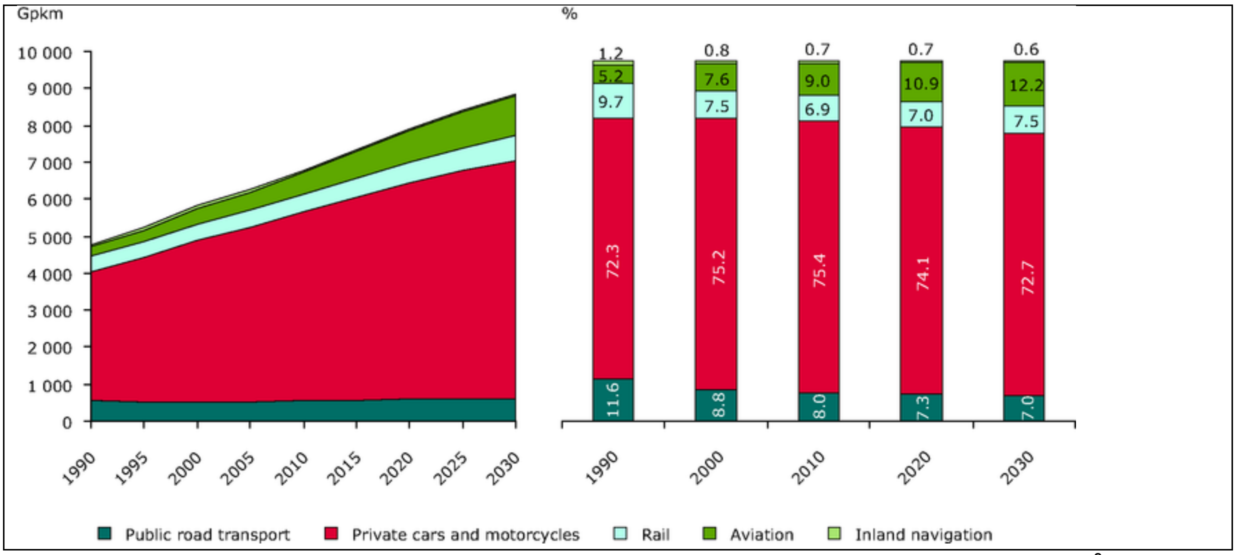

Figure 2-5: Modal development of passenger transport activities in Gpkm in EU25[8]

Road transport of passenger and goods clearly plays a predominant role in EU27 transport. In 2010, passenger cars (74%), powered two-wheelers (2%), buses and coaches (8%) accounted for 84% of total passenger transport performance. In 2010, each of the M502.5 EU inhabitants travelled a daily average of 35 km, 26 km of this by car. The total EU27 passenger transport performance, expressed in passenger-km, was 6,424 Gpkm in 2010. It has grown by 0.9% p.a. since 2000. The use of cars increased by 1.0% p.a. between 2000

6 http://ec.europa.eu/transport/themes/strategies/2008_greening_transport_en.htm, 21.07.2010

7 **In the following, a direct citing from the Internet is usually given at the end of the respective page, the date indicates the day of access to the site.**
Own depiction, data from: http://www.eea.europa.eu/data-and-maps/indicators/transport-final-energy-consumption-by-mode/assessment-4; 26.04.2015

8 http://www.eea.europa.eu/data-and-maps/figures/trends-and-outlooks-in-transport, 15.03.2013

and 2010. [Eurostat, 2012, p. 46] This dominant position of the car is explained by the advantages of flexibility, accessibility, comfort and costs, (see *Figure 2-18*).

The EU-forecast of the future modal structure of passenger transport is shown in *Figure 2-5*. **Private cars and motorcycles will remain the dominant transport means with an annual growth rate of +1.3%**. More specifically, total energy related passenger transport activity is projected to reach 8,861 Gpkm in 2030 (an increase of 1.5% p.a.).

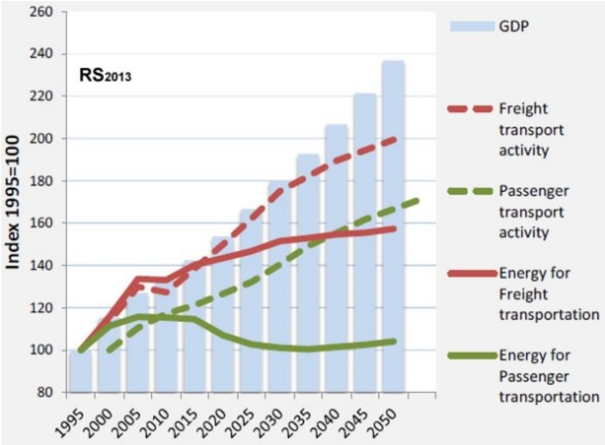

Figure 2-6: Policy impacts on transport energy consumption and transport activity [EC, DG Energy et.al., 2013, p. 40]

The energy efficiency of passenger cars increased in average by 2.11% p.a. between 1997 and 2012[9], i.e. more than annual GDP/inh. growth (1.3%) in EU27. [http://www.-stat.ee/29958, 29.03.2014] However, between 1990 and 2010, growth in passengers traffic, together with an observed modal shift from public transport to road transport, contributed to the increased total energy consumption from cars of 0.9% in average, offsetting part of the energy efficiency gains, see *Figure 2-10*. The impact of the CO_2-emission regulation and other structural changes imply considerable energy savings in the transport sector, especially close to 2030, (*see Figure 2-6*). A significant decoupling of passenger transport activity and energy consumption is expected. The transport sector displays some fuel switching. The share of biofuels rose to 4.6% in 2010. [Eurostat, 2012, p. 118] The biofuels share shall increase to 12% (RS_{2013}) by 2030. As a consequence, transport CO_2-intensityis expected to decrease.

In conclusion, government regulation and incentive setting in the energy and transport sector are strongly influencing investment decisions and market development. It is currently not clear how robust the current energy policy will be against energy and mobility price increases or changes in public acceptance. In addition, the fuel price development drives future transport energy consumption and use of transport modes. This will steer the direction of direct capital expenditure both on the demand and supply side. In 2020, total energy system costs will constitute 15% of the GDP, rising from 13% in 2010. Between 2020 and 2050, energy costs will continue to increase in absolute terms, but at a slower rate and below GDP growth, and the system will benefit from investments undertaken in the previous decade (notably via fuel savings). Energy system costs will reach 14% of GDP in 2030 and will return to 2010 levels in 2050. [EC, DG Energy et.al., 2013, p. 63] Thus, the critical phase is in a clear timeframe which is close enough to be quite predictable. The pay-back volume will strongly depend on the right decisions be made today.

2.2 World and European greenhouse gas emissions

The principal gases associated with climate change are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), which together accounted for over 99% of anthropogenic GHG-emissions in 2005. CO_2 is the dominant GHG, accounting for 64% of global and 83% of OECD countries' emissions in 2005, excluding land use and forestry emission sources and

[9] Measured as decrease of CO_2-emissions from 182 gCO_2/km in 1997 to 132 gCO_2/km in 2012.

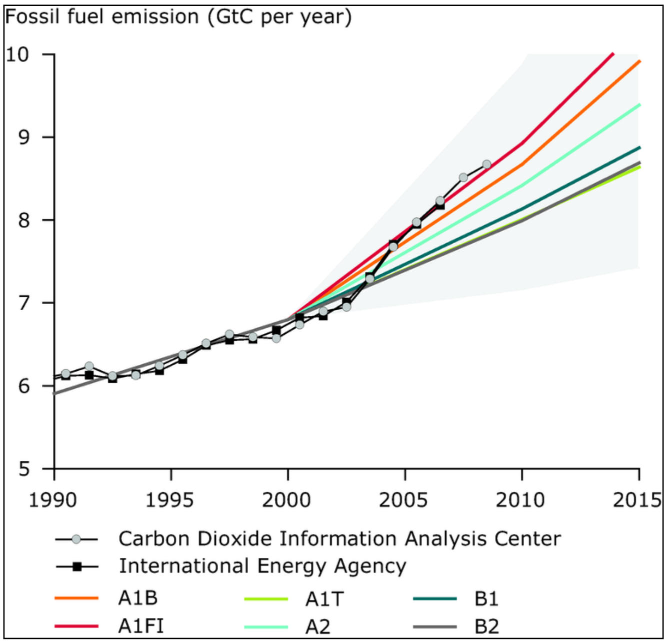

Figure 2-7: Observed CO_2-emissions vs. IPCC Scenarios[12]

sinks.[10] Energy accounts for two-thirds of world-wide GHG-emissions (2011). Within the energy sector, power generation (41%) is the main emitter, followed by transport (22%), industry (20%) and residential use (6%). [IEA, 2012, p. 9] The UNEP Emissions Gap Report 2012 found that current annual global emissions are around 50 $GtCO_{2eqv}$/a, already substantially higher than the estimates for 2020; consistent with the 2DS's goal (44 $GtCO_{2eqv}$/a). The 2020 gap would be 8 to13 $GtCO_{2eqv}$/a to the pathway of staying within the 2DS's climate target. [UNEP 2012, p. 4] In 2011, the IEA assessed that the achievement of its 2DS-goal would require CO_2-emissions to peak at 32.6 Gt/a no later than 2017, i.e. just 1.0 Gt above 2011 levels.[11]

The latest GHG-emission figures put global emissions on track with the worst case projections from the Intergovernmental Panel on Climate Change (IPCC) 2007 report, (see *Figure 2-7*), making it "extremely challenging" to prevent global temperature rising to dangerous levels. Furthermore, the IEA estimated that 80% of projected emissions from the power sector in 2020 are already locked in, as they will come from power plants that are currently in place or under construction. The five largest emitters are (shares in 2011 between brackets): China (29%), the United States (16%), EU27 (11%), India (6%) and the Russian Federation (5%), closely followed by Japan (4%). [Olivier et.al., 2012, p. 10]

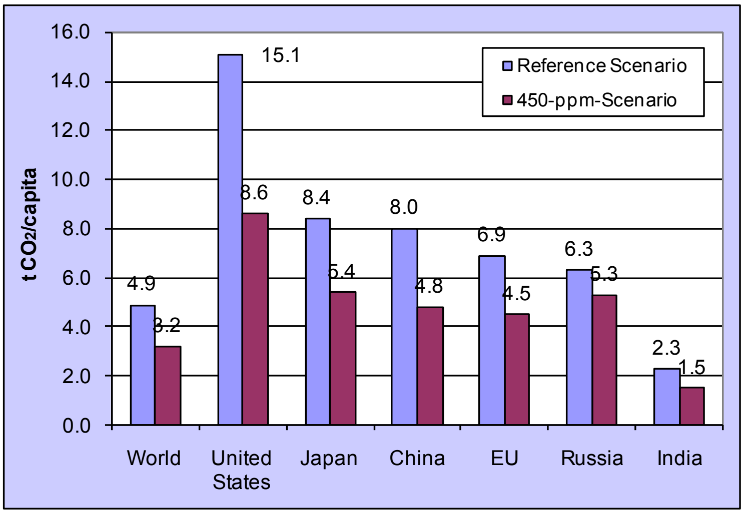

Figure 2-8: CO_2-emissions per capita in 2030 [IEA/ OECD, 2009, p. 17, 25, 29, 33, 41, 45, 53]

The comparison of the **CO_2-emission per capita** shows a quite clear picture, in particular when considering India (see *Figure 2-8*). In 2030, the average annual world per capita CO_2-emissions are predicted to be 4.9 t, with the US contributing 15.1 t/capita, China 8 t/capita, the EU 6.9 t/-capita and India only 2.3 t/capita (Reference Scenario). With a reduction of 16.2%, **EU27's CO_2-emissions** reached their lowest level in 2012, see *Figure 2-9*. CO_2-emissions are driven by increased energy efficiency in heat and elec-

10 http://www.eea.europa.eu/data-and-maps/indicators/ghg-emissions-outlook-from-mnp/ghg-emissions-outlook-from-mnp-1, 15.03.2013
11 http://www.iea.org/newsroomandevents/news/2012/may/global-carbon-dioxide-emissions-increase-by-10-gt-in-2011-to-record-high.html, 14.03.2013
12 http://www.eea.europa.eu/data-and-maps/figures/observed-global-fossil-fuel-co2, 21.02.2014

tricity production and transport, a shift from coal to less polluting fuels and by the economic downturn in the Eastern European Member States. The largest absolute CO_2-emission reductions took place in Germany, Romania and the United Kingdom, while the largest absolute increases were observed in Spain, The Netherlands and Greece. In 2012 in EU28, the energy industry (31%) and transport (21%) remained the largest GHG-emitters, followed by manufacturing industries (12%) and the residential sector (9%).

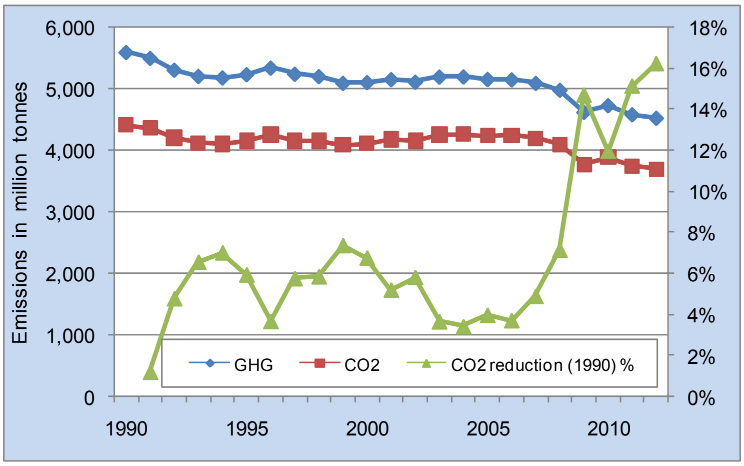

Figure 2-9: EU27 GHG-emissions[13]

Transport remains the sore spot of the climate protection policy. It is still highly dependent on oil derived fuels (95% in 2011) and the projected transport mode structure is characterised by the persisting dominance of road transport. Between 1990 and 2012, EU27 road transport GHG-emissions increased by 17% due to high growth both in road passenger and freight transport.[14] However, since 2007, road transport GHG-emissions are slowly decreasing. Also CO_2-emissions from passenger transport started to decrease in 2008, (see *Figure 2-10*).

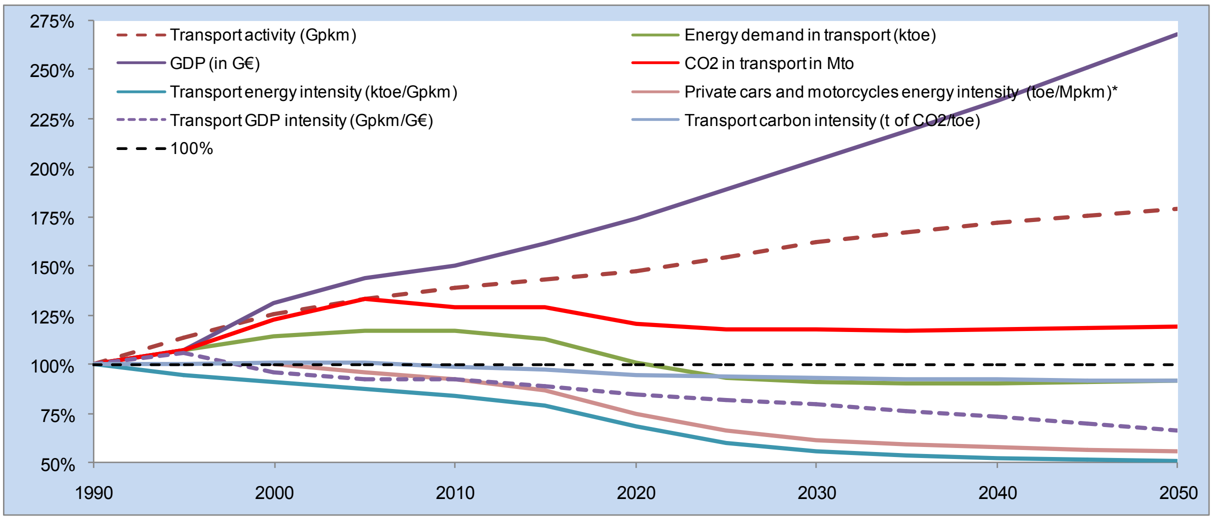

*Figure 2-10: RS2013 impacts on transport system [EC, DG Energy et.al., 2010, p. 41; EC, DG Energy et.al., 2013, p. 88-89] (*base year 2000)*

The policies implemented in RS_{2013} will lead to a decoupling of the transport energy demand from the transport activity. In particular fuel efficiency gains driven by LDV-CO_2-standards and high fossil fuel prices will result in significant CO_2-emission reductions relative to current trends, with the highest reduction taking place in the period 2010-2020. **Beyond 2035, CO_2-emissions from passenger road transport stabilise with no further tightening of CO_2-standards assumed,** see *Figure 2-10*. [EC, DG Energy et.al., 2013, p. 52] **However, overall transport GHG-emissions are expected to increase by 19% until 2050 compared to 1990 (RS_{2013})**. Decreases in carbon intensity of energy consumption are less pronounced as

[13] http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer, 19.06.2015

[14] http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer, 19.06.2015

the RS_{2013} projections do not show a significant shift towards alternative fuels. (It assumes 10% in transport by 2020, 12% in 2030 and 13.9% in 2050). According to RS_{2013}, hybrid cars make significant inroads, but there will be no significant use of electricity in road transport. PHEVs will represent about two thirds of grid-EVs by 2050. Other forms of energy such as LPG and CNG maintain a rather small share in the final energy demand of the transport sector (about 7% in 2050). [EC, DG Energy et.al., 2013, p. 42]

2.3 Climate change, air quality impact and external costs of transport

Climate Change is defined as a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes, external forcings or persistent anthropogenic changes in the composition of the atmosphere or in land use. **Climate Extreme**, i.e. extreme weather or climate event is the occurrence of a value of a weather or climate variable above a threshold value near the upper (or lower) ends of the range of observed values of the variable. [IPCC, 2012, p. 4]

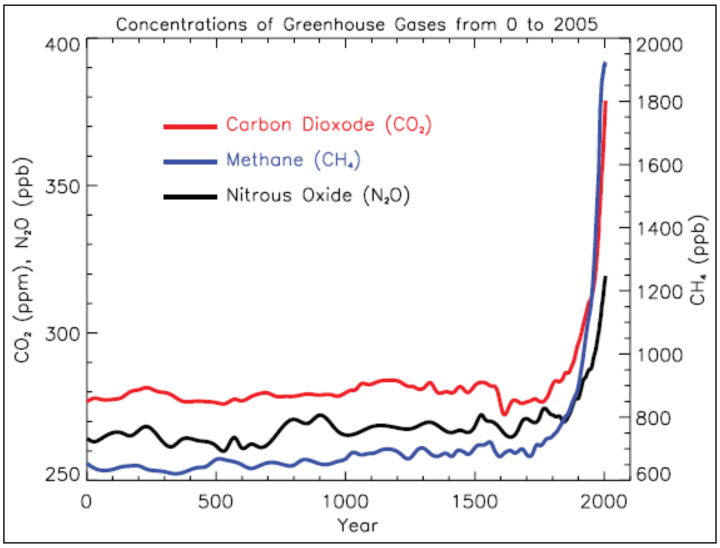

Figure 2-11: Atmospheric GHG-concentrations over the last 2000 years [IPCC, 2007 (1), p. 8]

Global atmospheric concentrations of CO_2, CH_4 and N_2O increased markedly as a result of human activities since 1750, see *Figure 2-11*. The global CO_2-concentration increase is primarily due to fossil fuel use and land use changes, while CH_4-and N_2O-concentration changes are largely due to agriculture. The global atmospheric CO_2-concentration increased from a pre-industrial value of about 280 ppm to 392.6 ppm in 2012.[15] This is much more than the natural range over the last 650,000 years (180 to 300 ppm as determined from ice cores). [IPCC, 2007 (2), p. 2-3] On 9 May 2013, the daily mean CO_2-concentration in the atmosphere of Mauna Loa, Hawaii, surpassed 400 ppm for the first time since measurements began in 1958.[16]

Nowadays, the warming of the climate system is unequivocal, because there is evidence from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. 2014 was the warmest year on record, but even more alarming: nine of the hottest years on record since 1880 have occurred since 2002. The globally averaged combined land and ocean surface temperature data show a warming of 0.85°C over the period 1880 to 2012.[17] [IPCC, 2013, p. 3, 6] NASA found that glaciers outside of the Greenland and Antarctic ice sheets, repositories of 1% of all land

[15] Carbon Dioxide Information Analysis Center (primary climate-change data and information analysis center of the US DOE since 1982): http://cdiac.ornl.gov/pns/current_ghg.html most recent GHG data.

[16] http://www.enn.com/pollution/article/45964, 12.05.2013

[17] US National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) maintains the world's largest climate data archive, this includes analysis of climate anomalies and events: http://www.ncdc.noaa.gov/sotc/global/2014/13

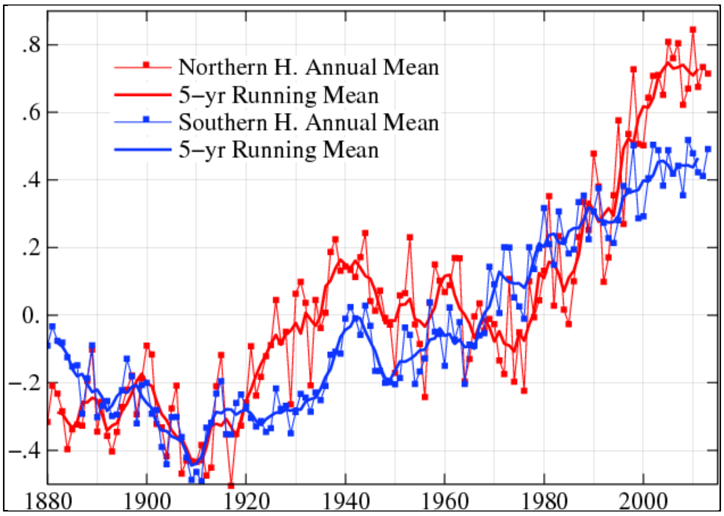

Figure 2-12: Hemispheric temperature change[19]

ice, lost an average of 259 Gt of mass p.a. between 2003 and 2009,making the oceans rise 0.7 mm/a.[18]

The World Bank warns in a recent report that a '+4°C world' would be so different from the current one that it comes with high uncertainty and new risks that threaten our ability to anticipate and plan for future adaptation needs. The '+4°C scenarios' include the inundation of coastal cities, increasing risks for food production potentially leading to higher malnutrition rates, unprecedented heat waves in many regions, especially in the tropics, substantially exacerbated water scarcity in many regions, increased frequency of high-intensity tropical cyclones and irreversible loss of biodiversity, including coral reef systems. [World Bank, 2013, p. ix] The possible 4-6°C range may also cause structural alterations to the weather patterns, possibly led by changes in important ocean currents such as the Gulf Stream. Already today, the economic impact of climate change are enormous; extreme weather events are responsible for five out of six natural disasters. For example, the Hurricane Katrina of 2005 caused costs of 125 GUSD, followed by the storm Sandy of 2012 with estimated costs of 65 GUSD.[20]

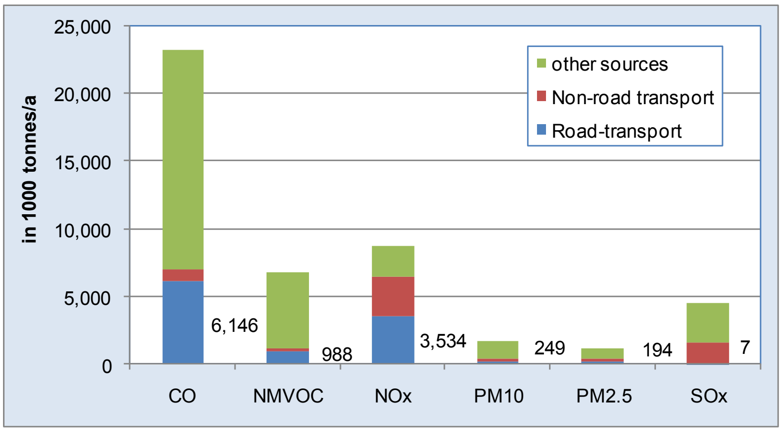

Figure 2-13: Air pollutant emissions in EU27 in 2011 in Gt[21]

Due to the success of the regulatory actions (Euro 1-6 standards) **transport borne air pollution** measurably decreased in Europe during the last 20 years, see Figure 3-1, even though traffic volumes continued to rise. A detailed European database of emission sources was implemented. Emission data are complemented by a dense network of air quality measurement points. Data are collected by the national authorities. The work is co-ordinated by the European Environment Agency (EEA) at EU-level. Background information on health and environmental effects is provided in the Air Quality Guidelines of the World Health Organisation (WHO) and the EEA respectively. *Figure 2-13* depicts the total emissions of the main regulated air pollutants in EU27 in 2011. Road transport contributes in particular to the NO_x- (40%) and CO-emissions

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18 The study compared traditional ground measurements to satellite data from NASA's Ice, Cloud, and Land Elevation Satellite and Gravity Recovery and Climate Experiment missions to estimate ice loss for glaciers in all regions of the planet. Data from NASA: http://www.nasa.gov/topics/earth/-features/glacier-sea-rise.html, 18.05.2013

19 Data from NASA: http://data.giss.nasa.gov/gistemp/graphs_v3/, 22.02.2014

20 http://www.ncdc.noaa.gov/billions/events, 14.12.2013

21 Own depiction, http://www.eea.europa.eu/data-and-maps/data/data-viewers/air-emissions-viewer-lrtap, 29.06.2014

(26%). PM-emissions from road transport originate mainly from the exhaust gas (61%), but also from automobile tyre and brake wear (22%) as well as automobile road abrasion (15%). In 2011, Germany missed its NO_x-ceiling by 80% and the NMVOC-ceiling by 5%, (set under the EU National Emission Ceilings Directive for SO_2, NO_x, NMVOC and ammonia to be kept by the year 2010). [Directive 2001/81/EC, 27.11.2001, §5] On a local level, the PM_{10} limit values of the Air Quality Directive are difficult to keep in some urban areas. The $PM_{2.5}$ limit values (25 µg/m³ by 2015 and 20 µg/m³ by 2020) are very demanding. During the period 1995-2010 total PM_{10} emissions from transport decreased to 57% of the initial value and $PM_{2.5}$-emissions to 48%. During the same period, NO_x-emissions were cut by more than half and CO-emissions declined to a quarter of the 1995 level. In 2014, 26% of newly registered cars in Germany complied with Euro 6, but only 29% of the vehicles in use complied with Euro 5. [kba, fz13, fz14, 2015]

Thus, reductions in the regulated emissions are occurring significantly faster than the emission increases resulting from growth in traffic volumes, i.e. total emissions of harmful substances to the air are decreasing. Nonetheless, further initiatives will still be needed to reduce people's exposure to damaging pollutants and to achieve the air quality targets set especially for NO_X and fine particles.

Internalisation of external costs such as climate change, air pollution and noise impact is one of the main focus points of the 2008 EC Greening Transport Package and of the 2011 EU White Paper on Transport. The monetary evaluation of external transport costs is complex and highly dependent on specific circumstances. Direct causalities are often difficult to define. For example, at night a noisy truck within a city has higher noise costs, while its contribution to congestion is small. The EEA estimated that the external costs of transport (excluding infrastructure and congestion costs) was 4-8% of GDP in the EU15 and made up to 14% of GDP in the new Member States in 2004. [EEA, 2004, p. 23]

The EC ordered an impact study to define the external costs of transport, i.e. the so-called CE Delft handbook (2008, updated in 2011). The CE Delft study provides a comprehensive overview of approaches, methods and default values for the estimation of external transport costs. It uses external cost categories of congestion-, accident-, air pollution-, CO_2-emission-, noise- and other costs. For details on the methodology and definition of the cost categories, please refer to the study itself. Its total and average cost estimates provide a basis for comparing the environmental burden of various transport modes. [Maibach et.al., 2008, p. 1]

The study calculated the external costs of car transport as 0.065 €/pkm. However, about half of these costs are caused by accidents (0.032 €/pkm) and could not be influenced by the use of zero emission vehicles. Between 0.003 and 0.017 €/pkm are allocated to climate change and 0.0055 €/pkm to air pollution costs. **This would result to climate change and air pollution costs of about 75 G€/a in EU27.**[22] ACEA ordered expertise from the Institute for Transport Economics at the University of Cologne to critically review the methodology and the results of the CE Delft study (most points from critics were taken into account in the updated Delft study). [Baum et.al., 2008]

2.4 Vehicle production, vehicle fleet and motorisation in EU27 and Germany

Vehicle production is an international market. The world vehicle production (LDVs, HDVs, buses) broke the M80 vehicles mark in 2011. It underwent a continuous growth, despite the

22 Estimation: M502 EU-inhabitants, 26 pkm/d, 365 d, 0.01 €/pkm climate change, 0.0055 €/pkm air pollution costs = M502 p *26 pkm/(p,d) *365 d/a *0.0155 €/pkm= 75 G€/a

crisis years of 2008/2009 and has increased by 49% since 2001. Until 2010, EU27 was the world's largest vehicle producer with an output of over M18 passenger cars, vans, trucks and buses per year (annual average 2006-2009), this was 22% of the world-wide vehicle production. In 2010, for the first time ever, China produced more vehicles (M18.3 vehicles, 23% of world production) than EU27, powerfully increasing its production 20-fold between 2001 and 2010. Also, India's car production has strongly increased and quadrupled over the last ten years. US car production has caught up its pre-crisis level again. The automobile industry is a leading EU export sector with a net trade contribution of 57 G€. Cars make up 90% of vehicles produced by the European automotive industry. There are 16 major car, truck and bus manufacturers in Europe operating 169 vehicle assembly and engine production plants. The European automotive industry provides M2.3 direct jobs (7% of the jobs in the manufacturing industry) and another M10.4 in directly related manufacturing (M1.2), automobile use (M4.2) and the transport sector (M4.9). [ACEA, 2011, p. 25 – 27, 38]

In the EU27, the number of passenger cars grew at an average rate of 2.3% p.a. from 1990 (M163) to 2010 (about M239). Germany is one of the leading automobile nations. Naturally it has, compared with other industrialised countries, a high motorisation rate (517 cars/1,000 inhabitants). On average, each of the M40 German households disposes of 1.05 car. [Eurostat, 2012, p. 41, 83] In 2014, M43.4 cars were registered in Germany. In general, the Germans have a stable affection to their vehicle segments as well as to their motorisation category. In Germany, compact and mid-sized cars dominate the new vehicle registrations with a share of 39%. SUVs are also still strongly requested (17%, 2014). This segment shows a particular large model variety. [kba, fz11, 01.05.2015]

Year	Displace-ment [ccm]	Power [kW]	Maximum speed [km/h]	Empty weight [kg]	[kW / 100 kg]
2001	1,849.0	83.6	186.7	1,331.3	6.3
2003	1,853.6	87.1	188.5	1,381.2	6.3
2005	1,856.0	90.7	189.1	1,426.2	6.4
2007	1,870.0	95.9	191.4	1,445.4	6.6
2009	1,669.5	86.8	186.0	1,296.9	6.7
2011	1,766.6	99.4	193.7	1,471.9	6.8
2013	1.732,2	101.0	194.6	1.474.9	6.8

Figure 2-14: Average characteristics of newly registered cars in Germany [kba table 1, 01.05.2015]

Power, maximum speed and weight of newly registered passenger cars in Germany have been steadily increasing, see *Figure 2-14*. The power-to-displacement-ratio increased from 0.045 in 2001 to 0.058 in 2013, representing the trend to engine downsizing. The average CO_2-emission of newly registered cars was 132.8 g/km (2014). Notably, diesel vehicles have a higher averageCO_2-emission (135.2 gCO_2/km),because of their high share in the large vehicle segments. [kba, fz8, 01.01.2015] The increasing vehicle mass is counteracting the attempts for fuel reduction.

With more than k27[23] newly registered cars in 2014 HEVs (see *Figure 2-15*) reached a total share of 0.24% of the overall car fleet (k108 HEVs). All other alternative technologies do not achieve considerable registration number increases. Nonetheless, CNG-registration numbers recently increased, manufacturers developed new models and are doing better advertising. The increasing registration numbers of alternative vehicles result in a slow rise of the total number of these vehicles on the streets (see *Figure 2-16*). However, diesel (30%) and petrol (68%) still represent the majority of cars in use and less than two of 100 cars are propelled alternatively, mainly with LPG (1.1%). LPG cars are mainly converted, thus registration and cars in-use numbers do not correspond.

[23] Translates to kilo 26 cars or 26,000 cars.

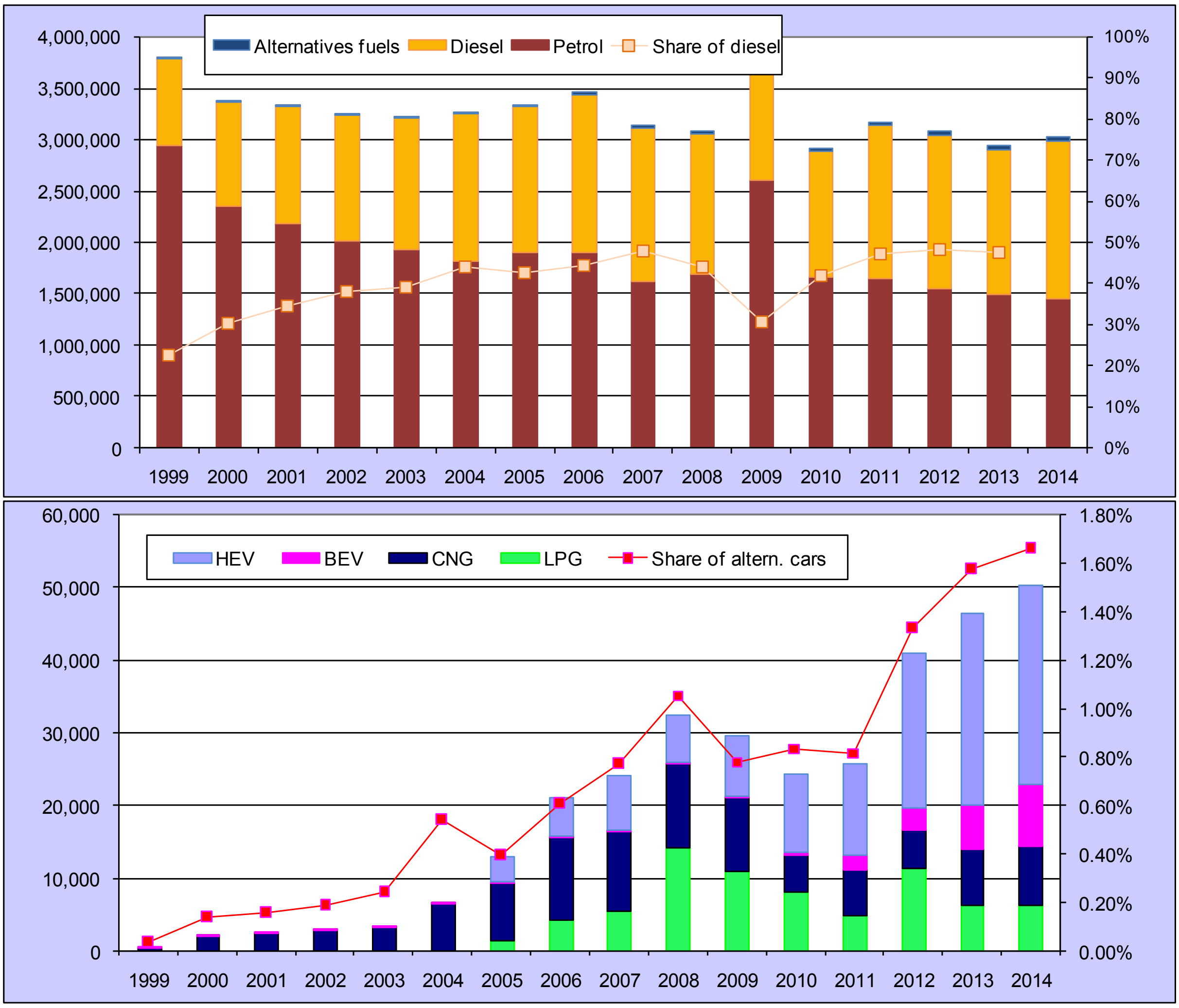


Figure 2-15: New vehicle registration according to fuel in Germany, 1999-2014[24]

Several scenarios exist predicting developments in the future car market based on new registrations in Germany and Europe, scenarios are compared in *Figure 2-17*. The scenarios on the future vehicle market are either based on the number of new registrations or on fuel consumed. All scenarios agree on the **increasing importance of diesel** fuel compared to petrol. The **use of biofuels** is limited in RS_{2013} to less than 10% due to the sustainability debate, the Delphi analysis (see section 6.3), even assumed a share of 17%.

The $Shell_{altern.}$[25] scenario predicts a share of 15% of conventional liquid fuels in 2030, the $EU15_{IEA}$ of 14.7%. The $Shell_{altern.}$ scenario predicts an early shift towards more efficient cars: **Hybrids** account for more than 20% of the new registrations already by 2020 and 50% by 2030. The Delphi analysis assumed a hybridisation rate of 38% by 2030. The market share of HEVs will grow on the cost of both petrol and diesel vehicles. In the $Shell_{altern.}$ scenario both will retain a market share of 17% each (about 36% each in the $Shell_{trend}$ scenario). The share of electricity is 4.9% in $EU15_{IEA}$ compared to 6.2% $World_{IEA}$ and 1% in $EU27_{RS2013}$. Nonetheless, 85% ($Shell_{altern.}$ scenario) or 80% (Delphi-analysis) of all newly registered vehicles will still have an ICE using petroleum based fuels by 2030. The share of petroleum-based fuels is 80.2% ($World_{IEA}$), 80% $EU15_{IEA}$ or 85.5% $EU27_{RS2013}$. **Consequently, the**

[24] In 2006, the distinction between mono- and bivalent vehicles was given up, instead gas vehicles are classified according to LPG and CNG, BEVS and HEVs were included. The enlistment of vehicles with rotary engine was given up. [kba fz13], 01.05.2015

[25] The predictions on future energy efficiency in the Shell scenarios are already outdated today.

$EU27_{RS2013}$ is not fulfilling the EU-CO_2-targets. By 2050 CO_2-emissions from energy use will decrease to 58% of 1990 levels, but the CO_2-emissions from transport increase by 19% compared with 1990 levels.

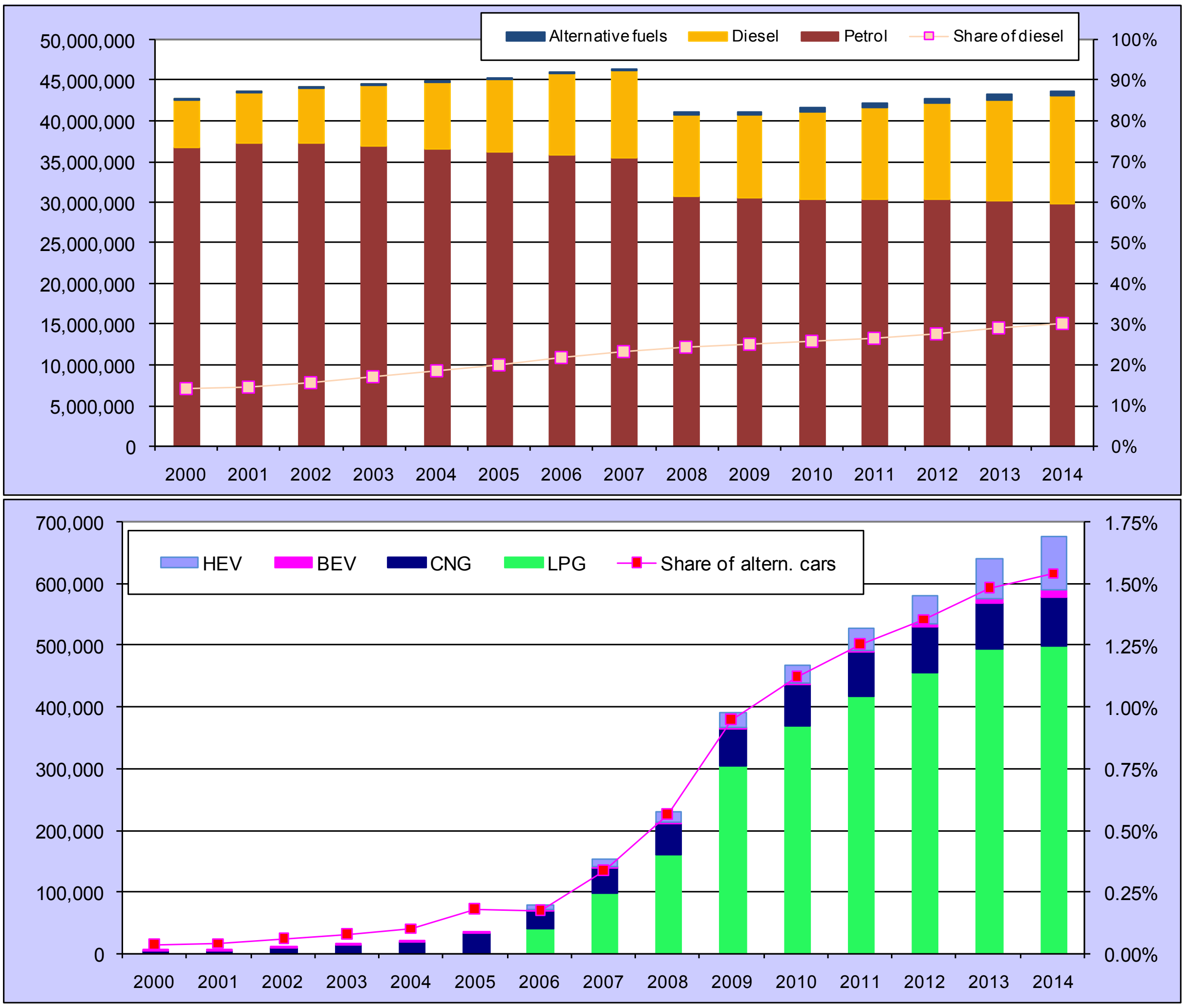


Figure 2-16: Vehicles in use according to fuel in Germany, 2000-2014[26]

CNG and LPG cars play only a minor role in all scenarios (together less than 6% of the new registrations in the Delphi-analysis), because they still use fossil fuels or have to compete for biomass. (Most studies do not include the use of biogas!) The CNG-share is 1.6% ($World_{IEA}$) and 0.4% $EU15_{IEA}$. However, the share of LPG and CNG significantly increased in the $EU27_{RS2013}$ scenario to 7%. This is not reflected by current trends. **Electric vehicles** will only enter the vehicle market slowly. BEVs will reach a share of 7% in the Delphi-analysis by 2030; this is an average value compared to the other scenarios. The **IEA_{450ppm}**-prospects on CO_2-intensities are 90 gCO_2/km ($World_{IEA}$) or 70 g CO_2/km ($EU15_{IEA}$). The Shell study also analysed the future mobility in Germany. Important factors are the demographic development, gender and age group aspects. From 2020 onwards Shell predicts a decrease in the total number of private vehicles due to fewer people of an age capable of running a car in Germany. During the same period, the share of cars in corporate ownership will increase from 9.3% to 10%. The total number of cars will rise to M49.7 in 2020, when it will stagnate. [Shell, 2009, p. 25] In contrast, the EC foresees a significant expansion of car sales in the EU, which will lead to a motorisation rate of 710 cars/1,000 inhabitants in 2030, up from 470 in 2008 and 350 in 1990. [EC, COM (2008)19, p. 53; ACEA, 2011, p. 4]

[26] Since 01.01.2008 without temporary decommissioned vehicles. [kba fz13, 01.05.2015]

			2020				2030					
	Germany		Germany			EU27	Germany			EU15	EU27	World
	2002	2012	Delphi	Shell trend	Shell altern.	RS 2013	Delphi	Shell trend	Shell altern.	IEA 450 ppm	RS 2013	IEA 450 ppm
Petrol %	61.9	50.5	46	42.3	35.1	39	38.0	36.7	17.0		32	
Diesel %	38.0	48.2	46	48.5	41.0	46	40.0	36.8	17.5		50	
Hybrid petrol or diesel %	0.0	0.7		5.5	17.4			20.0	50.0			
LPG %	0.0	0.4	1.7			3+	2.5	2	2		3.5+	
Subtotal petroleum based	**99.9**	**99.7**	**93.7**	**96.3**	**96.8**	**88**	**80.3**	**95.5**	**86.5**	**80.0**	**85.5**	**80.2**
CNG%	0.0	0.2	1.9			3+	3.3	2	3	0.4	3.5+	1.6
BEV/Electricity%	0.0	0.1	3.1			0>	7.2	2.5	10.0	4.9	1	7.5/6.2
Hydrogen %	0.0	0.0	1.8				8.0					
Biofuels %			10.6			8	17.1	10	15++	14.7	9	12.0
Others %	0.0	0.0			3.2		1.1	4.0	5.5			
Hybridisation rate %	0.0	0.7	15	5.5	17.4		37.7	20.0	50.0	35		50*
CO_2g/km		141.8						143 (petrol)	136 (petrol)	70		125

Figure 2-17: Comparison of future vehicle market scenarios (new registrations, fuel share)[27]

Another trend influencing the mobility patterns is increasing urbanisation, see section 3.5. A survey from 2009 showed that, in particular, young people in urban areas are more willing to abstain from vehicle ownership. [Linz et.al., 2011, p. 16] The reasons are manifold, a long lasting factor may be that the renunciation of car ownership reflects a change in lifestyle and the way of thinking about the status of car ownership. The value preferences of the youth towards the car are changing away from enthusiasm for automobiles to more personal mobility concepts. As a consequence, the younger generation obtains the driving license later and car ownership became one interest among others. [Kruse, 2009, p. 13-17] The future motorisation of the young generation will influence the overall motorisation in the long-term, because people normally keep their general motorisation attitude for a long time. [Shell, 2009, p. 21-23] The automotive industry has to encounter the climate debate, the high oil prices **and** a product policy which concentrates on large, highly motorised and heavy premium vehicles, which does not reflect this change in values and status-thinking. In parallel to the downfall of the emotionally experienced added value of premium vehicles the desire to own a car is decreasing. Car-sharing or rental concepts are gaining attractiveness. The success of personal public transport solutions such as car2go[28] illustrates this development. The number of car-sharing users is increasing continuously.

The vehicle's Total Cost of Ownership (TCO)[29] will influence the future rate of fleet renewal, the disposition to buy a car at all or the willingness to use an alternative transport mode. The costs for mobility made up around 13% of private expenditure for consumables in Germany in 2005 (basis year). The use of the own car made the largest share (86%) of this expenditure, only 14% were spent on public transport (7% local public transport, 3% rail transport, 2% air transport, 2% others). [Linz, et.al., 2011, p. 16] The German 'driver index'[30] increased by 45 percentage points between 2005 and 2014. For comparison, the consumer

27 Shell Deutschland Oil, 2009, p. 30-33; IEA/OECD, 10/2009, p. 18, 30; EC, DG Energy, 2013, p. 42; +RS2013: LPG and CNG together: 6% in 2020 and 7% in 2030; ++ no biogas

28 Car2go is a car sharing concept on membership basis. Within a defined area cars may be hired and parked without any restrictions and the necessity to come back to the starting point. Car use is invoiced as a per minute price. Cars may be booked by using the smart phone.

29 TCOs add other costs expected to be incurred during the vehicle life to the initial purchase price, such as fuel, service, repair and insurance costs.

30 It includes the price of new and second hand cars, motorcycles, spare parts, care products, maintenance, inspection/repair as well as cleaning.

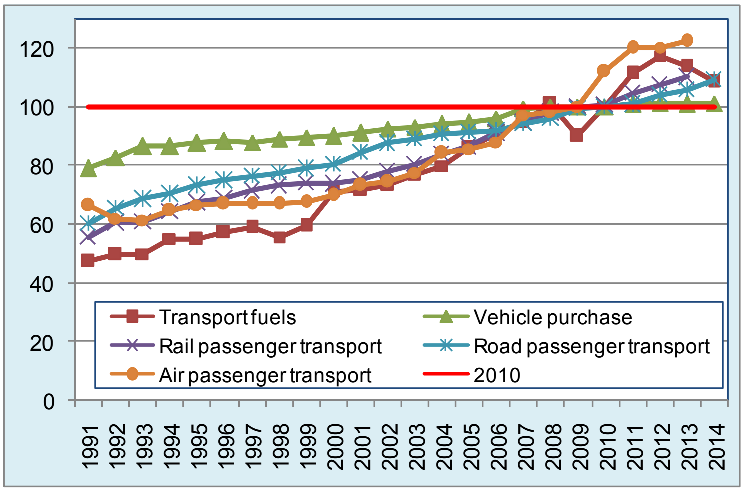


Figure 2-18: Development of various price indices [*Statistisches Bundesamt: 2015, p. 70, 76, 166*]

price index increased by 36 percentage points during the same period. Fuel costs increased by 61 points, but the costs for new cars increased only by 22 points (2005-2014) and the cost of public rail transport increased by 58 points. [Statistisches Bundesamt, 2015, p. 154 et seq.] At the same time, due to heavy investment in efficiency technologies the average vehicle CO_2-emissions decreased by more than 27% between 2000 and 2013 (EU15).

The **infrastructure development** will also play a crucial role for the market introduction of alternative fuels. Any filling station network has to be area-covering, but also needs a sufficient capacity utilisation to allow profitable operation. After a strong and long consolidation process, there are less than k15 filling stations in Germany today (compared to a maximum number of more than k46 filling stations in 1969[31]). This equals a utilisation rate of about k3 cars per filling station.

Despite an aging population and a higher urbanised youth with less interest in owning a car, the current prospects for GHG-reduction from transport are poor. Currently there are only vague concepts for freight transport available, but also the fleet standards for cars and vans currently applied are not strict enough to sufficiently reduce the climate impact of road transport. Only a continuation of the ECs CO_2-fleet standards could change this situation for the car segment. The prices of new vehicles increased only slightly compared to other products despite the large technology innovations to reduce air pollutants and climate gas emissions between 1991 and 2014. However, the EU's Delft study still estimates external costs from climate change and air pollution in the range of 15.50 €/k (kilo)-pkm.

31 http://www.adac.de/infotestrat/tanken-kraftstoffe-und-antrieb/probleme-tankstelle/anzahl-tankstellen-markenverteilung/; 20.06.2014

3 Market framework conditions

This section describes the political and economic framework conditions within which decisions are made by investors and users of H_2- and FC- (H_2FC)-technology[32]. The policy framework constitutes the most important driving force for the market introduction of H_2FC-technologies setting the institutional, legal, fiscal and political general conditions. Furthermore, it substantially influences societal attitude towards the technology. The economic surrounding, described by the price and availability of competing fuels and technologies, the need for transportation and energy of a growing population and the wealth of the society, decisively determine the prospect of success of the technology. The economic driving force is of utmost importance for the market penetration of H_2FC-technologies as economic effectiveness is a precondition for any investment in significant numbers of vehicles and in a dedicated infrastructure.

The policy and economic framework is mainly set at a European level because the majority of the respective environmental and energy legislation is currently made at European Union level. If concrete national examples are given, Germany is usually referred to, because Germany is the selected key market for H_2FC-transport technologies in this thesis. If requisite, US regulations are outlined, because the H_2FCV-market introduction needs a market large enough to justify the huge efforts for technology development.

3.1 The general policy and legislative framework

The ‘right’ policy framework has an enormous impact on the development of new technologies, in particular on research, development and initial deployment activities. The right incentives may significantly reduce the time for commercialisation of new technologies and thus support or even enable their market breakthrough. Policy incentives for the promotion of H_2-fuel should address the supply **and** demand side, taking into consideration issues of global competitiveness of the H_2FC-industry and public benefit. They should **reward technologies proportionate to their ability to meet policy (societal) objectives**.

The policy objectives should be transparent and should be based on scientific results using a sound analytical approach. An “**Impact Assessment Guideline**” shall improve the quality of European Commission’s (EC) regulatory proposals. This comprehensive impact assessment should be undertaken at an early stage of policy development, accompanying the legislation process and enabling evidenced-based decision making. [http://ec.europa.eu/governance/-impact/aims_en.htm, 09.09.2007] Regulation should be **cost-effective** and should have the capacity to solve problems with feasible costs within the lead-time, i.e. the period of time required by the parties concerned to prepare for a certain level of compliance with the new regulation. Any lead-time for existing vehicle types shall be established in accordance with the respective product and development cycles. [EC, DG Enterprise and Industry, 2006, p. 20] In addition, regulation shall put European companies in a good starting position for the exploration of advanced technologies such as renewables and H_2FC-technology (hydrogen is accounted for as a renewable fuel in the terminology of the EC, because renewable production is assumed in a mature market). Innovation offsets shall lower the net costs of meeting environmental regulations and improve competitiveness over non-EU companies being not subject to similar regulation. **Innovation offsets** are realised when any reduction of pollution is combined with productivity improvements. [EC, DG Enterprise and Industry, 2006, p. 18–21] Government action to support H_2FC-technologies include:

[32] Section 4.2.4 will demonstrate that hydrogen fuel and FCVs are indispensably interlinked today.

- Setting regulations which support or hinder the development of certain technologies, e.g. US ZEV and EC CO_2-fleet standards, US and EC regulations for alternative fuel infrastructure development, international and national climate programmes, see section 3.2.
- Support to R&D in vehicle and infrastructure design, planning and assessment of viability, e.g. Framework Programmes, NIP, NEP and direct participation in initiatives steering or at least influencing the content of discussion, e.g. German CEP, NPE, see section 4.1.
- Direct or indirect fiscal and financial support for demonstration projects, e.g. funding, fuel duty and vehicle tax rebates, road tolls and enhanced capital allowances, see section 3.3.
- Promotion of energy efficiency, air pollution and GHG-reduction to stimulate the demand for clean transport and stationary H_2FC-applications, including labelling.
- Assessment of the scope and effectiveness of policy measures and removal of regulatory barriers to the commercialisation of H_2FC-applications.
- Development of codes and standards to support initial deployment and commercialisation. including the simplification and harmonisation of planning and certification requirements (e.g. fuel and safety standards, licensing of equipment and sites).
- International coordination of policies and deployment strategies. [HLG H_2FCs, 2003, p. 17]

In the following, the main policy actions which support the market introduction of hydrogen as a fuel are described. These are mainly European activities, but also include some international or national actions. Most of these actions were not developed to promote the H_2-economy in particular, but are targeted at more general policy objectives such as increased energy security, climate protection or the improvement of air quality, see Figure 3-1.

International agreements or conventions
United Nations Framework Convention on Climate Change (UNFCCC), Rio de Janeiro 1992 with the ultimate objective (approved by the European Community by Council Decision 94/69/EC, 1993): “to achieve […] stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic (human induced) interference with the climate system. Such a level should be achieved within a time frame sufficient to allow the ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable development to proceed in a sustainable manner." (Article 2 of the UNFCC)
The **Kyoto Protocol,** Conference of the Parties (COP3), Kyoto 1997, entered into force on 16.02.2005 after Russia’s ratification[33]. Today, there are 192[34] Parties to the Protocol. Most industrialised nations and some central European economies agreed to legally binding reductions in GHG-emissions below 1990 levels between 2008-2012, the **first emissions budget period**. The individual countries’ emission reduction targets ranged from -8% (EU15-target) to +10% and added up to an overall -5% target for developed countries. [BMU, 2006, p. 16-17]
Intergovernmental Panel on Climate Change’s (IPPC) Fourth Assessment Report, 2007” assured a direct relationship between the activities of mankind and climate change for the first time: “Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations. This is an advance since the TAR’s [Third Assessment Report] conclusion that ‘most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations’. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns […]” [http://www.ipcc.ch/publications_-and_data/ar4/wg1/en/spmsspm-understanding-and.html, 23.3.2013]
Cancun 2010, COP16, commitment to **a maximum temperature rise of 2°C** above pre-industrial levels and to consider lowering that maximum to 1.5° in the near future. According to the 4th IPPC report, this would call for GHG-reduction by at least 25-40% below 1990 levels by 2020.

33 Ratification required at least 55 of the Parties to the UNFCCC, which together account for at least 55% of CO_2-emissions from industrialised countries in 1990.

34 http://unfccc.int/kyoto_protocol/status_of_ratification/items/2613.php, 23.02.2014

Doha 2012 (COP18), "**Doha Amendment to the Kyoto Protocol"**: 37 Parties[35] committed to reduce GHG-emissions by at least 18% below 1990 levels between 2013 to 2020.[36]
European energy and transport policy for climate protection
The European Councils of Environment and Energy (1990) agreed on a stabilisation of the total CO_2-emissions at 1990 level in the EU by the year 2000. A strategic EC proposal (1992) **targeted at reducing CO_2-emissions by 12% compared to 1990 level until the year 2000**, incl. a set of measures.[37]
Framework Directive 93/76/EEC to promote energy efficiency (SAVE)
Council **Decision 93/389/EEC** established an **EU monitoring system for CO_2- and other GHG-emissions** for supervising national CO_2-reduction targets. Today, it has emerged to a comprehensive database which allows to follow the effects of policy measures. Data, maps, indicators and reports are published on the homepage of the European Environment Agency (EEA)[38]. In 2013, the EEA provided a report assessing the progress of the EU and European countries towards achieving their climate mitigation and energy policy objectives. [EEA, 2013]
The **European Climate Change Programme** (ECCPI, 2000-2004; ECCPII, 2005) was aimed at developing an EU strategy for implementing the Kyoto protocol identifying 42 possible measures which could lead to some 664-765 $MtCO_{2eq}$ emission reductions against costs less than 20 €/t CO_{2eq}.[39]
The **'Lisbon Strategy'** (2000) was launched during the European Council meeting in Lisbon. It aimed at making the EU the most competitive economy in the world and achieving full employment by 2010. An **environmental pillar** was added at the Gothenburg European Council meeting in 2001, drawing attention to the decoupling of economic growth from the use of natural resources.[40]
The **Sustainable Development Strategy** (2001, revised in 2005) addressed combating climate change as a major priority. It foresaw breaking the link between economic and transport growth to ensure a sustainable transport.[41]
European Parliament and Council (2005) reaffirmed the EU **objective that global surface temperatures should not rise by more than 2°C** compared with pre-industrial levels in order to prevent dangerous and irreversible anthropogenic climate change. [EC, COM(2007)19, 07.02.2007, p. 3]
The "**Green Paper - towards a European strategy for the security of energy supply**" (2000) [EC, COM(2000)769 final, 29.11.2000] launched a debate on the geopolitical, economic and environmental stakes involved in the increasing dependence from energy imports to the EU. In the transport sector, the use of fuel substitutes was targeted at 20% in 2020.
The "**White paper - European transport policy for 2010: time to decide**" (2001). [EC, COM(2001)370, 2001] targeted a **20% use of fuel substitutes (biofuels, natural gas vehicles, in the long term hydrogen) by 2020**. Followed by: "Green Paper - A European Strategy for Sustainable, Competitive and Secure Energy" (2006) [EC, COM(2006)105final, 8.3.2006]; "Green Paper on Energy Efficiency or Doing More With Less" (2005) [EC, COM(2005)265 final, 22.6.2005].
The "**Climate Action and Renewable Energy**" package, European Council 2009, includes as part of the "**Integrated Energy and Climate Change**" programme the **20/20/20 target, i.e. a 20% GHG-emission reduction (or by 30%, if the conditions are right; base: 1990 levels), a 20% share of renewable energy in final energy consumption and a 20% energy efficiency** increase by 2020. The latter is a non-binding target.

35 EU27, Australia, Belarus, Croatia, Iceland, Kazakhstan, Liechtenstein, Monaco, Norway, Switzerland, Ukraine

36 http://unfccc.int/kyoto_protocol/items/2830.php, 26.03.2013

37 The 12%-target was reached only in 2010. [EC DG Energy, 2010, p. 66]

38 http://www.eea.europa.eu/data-and-maps/indicators/#c5=&c7=all&c0=10&b_start=0, 26.03.2013

39 http://ec.europa.eu/environment/climat/first_phase.htm; 13.05.2012

40 http://ec.europa.eu/archives/growthandjobs_2009/, 08.11.2015

41 http://ec.europa.eu/environment/integration/integration_update.htm, 24.03.2008

The "**Europe 2020 Strategy**", 2010, targets a smart, sustainable and inclusive growth. [EC, COM(2010)2020, p. 5-6, 11, 14]
The initiative "**Resource efficient Europe**" (COM2011(21)) should finally lead to the decoupling of economic growth from the use of resources, support the shift towards a low carbon economy, increase the use of RES, modernise the transport sector and promote energy efficiency. It reaffirms the **20/20/20 target** and recognises that climate goals can only be achieved, if emissions are reduced significantly and more quickly in the next decade.
"**Roadmap for moving to a competitive low carbon economy in 2050**", COM2011(112) includes an overall climate reduction target of 80% (below 1990 levels) and a transport sector target of 60%.
The White Paper "**Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system**", 2011, focuses on scarce oil resources, the cost of oil imports (about 210 G€ in 2010) and limiting climate change below 2°C: It **asks for a reduction of transport GHG-emissions by 20% by 2030 and 60% by 2050 while supporting mobility**. It explicitly targets **halving the use of conventionally fuelled cars in urban transport by 2030 and to phase them out by 2050**. Large fleets are selected to be preferentially converted to alternative systems. Logistics in major urban centres shall be CO_2-free by 2030. An appropriate alternative fuelling or recharging infrastructure should be implemented. Road pricing and taxation to internalise externalities (with revenues used for the development of an efficient transport system) is envisaged. A regulatory framework for CO_2-standards emissions for vehicles of all modes, for noise emission levels, for refuelling infrastructures etc. shall be created. [EC, COM 2011/144 final, 28.03.2011, p. 3, 8-9, 12, 15, 25, 29] The EC's public consultation with its **Green Paper on "A 2030 framework for climate and energy policies"**[42] reflects the future use of nuclear energy (which could be used as a carbon neutral source for H_2-production), developments on energy markets, concerns about the affordability of energy and the varying levels of commitment of international partners in reducing GHG-emissions. [EC, COM(2011)169] "**A policy framework for climate and energy for the period 2020 to 2030**", 2014, sets a 2030 GHG-reduction target of 40%. This would need an increased level of energy savings of about 25% and translates to a fleet target of 71 gCO_2/km by 2030. Various GHG-reduction targets (35%, 40% and 45%) were assessed for their impact. The conclusions of the Energy Roadmap 2050 were confirmed: **the costs of a low carbon transition do not differ substantially from the costs that will be incurred in any event because of the need to renew an aging energy system as well as due to rising fossil fuel prices** and adherence to existing climate and energy policies. In any case, energy system costs are expected to increase over the period to 2030 to a level of around 14% of GDP compared to about 12.8% in 2010. The renewable headline target was set at 27%. However: "**the Commission does not think it appropriate to establish new targets for renewable energy or the greenhouse gas intensity of fuels used in the transport sector or any other sub-sector after 2020**." [EC, COM(2014)15 final, 2014, p. 4, 6, 8]
EU regulations to reduce air pollutant emissions from passenger cars
Holders of EC **Type Approvals**, e.g. **Directive 70/156/EEC on type approval for motor vehicles** [...] (various amendments by now) enjoy the advantage of being able to bring their products on the EU internal markets without having to go through further national approval procedures.
Directive 70/220/EEC sets light vehicle emission limit values; i.e. Euro 6 standards are applicable for newly registered M-category-vehicles since 2014/2015. [EC Regulation 715/2007] Emissions and fuel consumption are measured using a chassis dynamometer test on the so-called **New European Driving Cycles (NEDC)** [Directive 93/116/EC, Regulation (EC) 692/2008]. In addition to the mass-based PM standards, the EC is asked to adopt a number-based PM-standard in order to better control ultrafine PM-emissions (PM 0.1 µm and below). These EU regulations are also introduced with a certain time delay in Asia except in Japan, Taiwan and South Korea. [T&E, 2006, p. 11]
The **PHEV's fuel consumption** is determined according to regulation **UN ECE R101** on the NEDC. The vehicle runs the cycle twice. The weighted fuel consumption is calculated as follows (the consumption of electricity is neglected, consumption C1: full battery; consumption C2: empty battery):

42 http://ec.europa.eu/energy/green_paper_2030_en.htm, 16.12.2013

$C_w = (R_e * C_1 + R_c * C_2)/(R_e + R_c)$. [UN/ECE, 2012, 3.4.2.1]	C_W = Consumption weighted (fuel), R_e =Range electric R_c = Distance between two charges (set to 25 km)
Directive 98/70/EC set EU quality specifications for petrol and diesel used in road and other vehicles.	
Regulation (EC) 79/2009 established specific procedures, tests and requirements for type approval of hydrogen-powered vehicles (classes M and N) and integrated systems.	
Air quality regulation and noise abatement	
The **Air Quality Framework Directive** [EC, 96/62] listed pollutants for which air quality standards and objectives had to be developed. It asked the Member States to draw up a **list of zones and agglomerations** in which the levels of one or more pollutants are higher than the limit value plus a margin of tolerance. Member States have to maintain these standards and preserve the best ambient air quality compatible with sustainable development by drawing up short-term action plans for these areas. [EC, Directive 96/62/EC, 20.11.2003] A number of so-called supporting directives described thresholds for the management of certain air pollutants[43] which were elaborated in close co-operation with the stakeholders in the framework of AOPII. [EC, COM(2000)626 final, 05.10.2000, p. 6-7]	
Strategies to combat acidification, ozone and eutrophication were formulated, notably via **Directive 2001/81/EC,** setting national SO_2-, NO_x-, VOC compound- and NH_3-emission **ceilings** for each Member State. However, the 2010 ceilings are technically unfeasible to meet WHO guideline objectives for eliminating the adverse effects of acidification and to reduce exposure to ground-level ozone of man and environment. [EC, Directive 2001/81/EC, 27.11.2001, §5]	
"**The Clean Air for Europe (CAFE) Programme: Towards a Thematic Strategy for Air Quality**", 2001, laid the basis for the thematic strategies on clean air announced in the **Sixth Environmental Action Programme of the European Community entitled "Environment 2010: Our Future, Our Choice"** (2002-2012). It was targeted to achieve levels of air quality that do not give rise to unacceptable impacts on, and risks to, human health and the environment. [EC, Cafe Programme]	
The EC's **Thematic Strategy on Air Pollution**, 2005 aims to **cut the annual number of premature deaths from air pollution-related diseases by almost 40% from the 2000 level by 2020** and to substantially reduce the area of forests and other ecosystems suffering damage from airborne pollutants. While covering all major air pollutants, the Strategy pays special attention to particulates and ground-level ozone pollution because these pose the greatest danger to human health. The health benefits shall achieve at least 42 G€ p.a. through fewer premature deaths, less sickness, fewer hospital admissions, improved labour productivity etc. Costs are estimated at 7.1 G€/a. The number of premature deaths related to fine PM and ozone shall be reduced from k370 a year in 2000 to k230 p.a. in 2020. Without the Strategy there would still be over k290 premature deaths a year in 2020. The strategy resulted in the **New Air Quality Directive 2008/50/EC**.[44]	
The ECs Environment Action Programme entitled "**Living well, within the limits of our planet**" (2014-2020) aims to enhance Europe's ecological resilience and to transform the EU into an inclusive and sustainable green economy. Protecting natural capital, encouraging more resource efficiency and accelerating the transition to the low-carbon economy are key features of the programme, which also seeks to tackle environmental causes of disease.[45]	
The German Federal Immission Control Act (§§ 41 to 43), the Traffic Noise Ordinance (16th BImSchV) and the Road Noise Protection Regulation (24th BImSchV) regulate noise and its prevention. For example, the German noise limit in residential areas during the daytime is 59 dB(A) and 49 dB(A) at night. [Senatsverwaltung für Stadtentwicklung, 2005]	

Figure 3-1: Overview on international and European climate and transport legislation influencing the market introduction of H_2FCVs

43 SO_2, NO_2, NO_x, PM_{10}, $PM_{2.5}$ and lead (**Directive 1999/30/EC**), benzene and CO (**Directive 2000/69/EC**), ozone (**Directive 2002/3/EC**), Arsenic, Cadmium, Mercury, Nickel and polycyclic aromatic hydrocarbons (PAHs) (**Directive 2004/107/EC**).

44 http://ec.europa.eu/environment/air/index.htm; .../quality/legislation/directive.htm, 09.04.2010

45 http://ec.europa.eu/environment/newprg/, 18.06.2013

The EC started its climate protection activities just 20 years ago. In the meantime, targets, measures, decision maker information and monitoring systems have been implemented and the first results were achieved. The future climate protection working programme of the EU is challenging. Currently, political targets are only partly backed up with a comprehensive list of related legislation. A list of EU efficiency policy measures may be obtained from the latest RS_{2013}. [EC, DG Energy et.al., 2013, table 2] Today, short-term GHG-targets are binding, long-term GHG- and efficiency targets are formulated, but are still not binding. However, the EU energy and climate policy system is structured and political procedures are working and ongoing, this builds trust in a possible achievement of the future targets until 2030/2050. However, zero emission electrically propelled vehicles such as BEVs and FCVs can also contribute to the ambient air and noise targets.

3.2 Specific European and German legislation concerning the climate impact of road transport by cars

3.2.1 Community strategy to reduce CO_2-emissions from passenger cars

The EC adopted a **Community Strategy for reducing CO_2-emissions from cars** already in 1995 (COM(1995)689) as part of the ECCP. During the negotiation process with the car manufacturers, the original EU-target of **120 gCO_2/km** for new passenger cars to be reached by 2005 (resulting in a 35% reduction over 1995 levels) was weakened and postponed several times. [EC, COM(2007)856 final, p. 1] It took until 2007 to agree on a binding CO_2-car fleet target of **130 gCO_2/km** by means of improvements in vehicle motor technology for the EU25 for **2012** (COM(2007)19final). The strategy was accompanied by the labelling **Directive1999/94/EC** (amended by **Directive 2003/73/EC**) aimed to guarantee the availability of consumer information on fuel economy and CO_2-emissions. **Decision 1753/2000/EC** established a scheme to monitor the average specific CO_2-emissions from new passenger cars and requested some general technical measures to finally reach 120 gCO_2/km under real operation conditions such as tyre labelling. [EC, COM(2007)19, p. 6, 8]

Regulation 443/2009 set the final emission performance regulation for new passenger cars. After long negotiations it was agreed to limit vehicles' CO_2-emissions according to the average vehicle mass of the individual manufacturer, thus each manufacturer has its own target. A control parameter 'f' was introduced to avoid a potential incentive to increase the vehicle mass. However, the weight factor 'f' punishes weight reducing manufacturers, e.g. under the assumption that the overall average car mass remains constant in the EU, the individual limit value of a vehicle manufacturer who lightens its average car weight by 100 kg tightens by 4.57 gCO_2/km. Therefore, also the 'vehicle footprint' (the car's track-width times the wheelbase) was discussed as a good proxy for the vehicle's interior space. The precise formula for the limit value curve is: [EC, Regulation (EC) No 443/2009, Annex I]

CO_2 [g/km] = 130 + a x (M – M_0)	M = mass in kg[46]; M_0=f x 1.372 kg; a=0.0457 f = (1 + Autonomous Mass Increase %)

The fleet target is phased-in: the **compliance timeline** asks that 65% of each manufacturer's newly registered cars must comply with the individual target by 2012. This has risen to 75% in 2013, 80% in 2014 and 100% from 2015 onwards. Regulation 443/2009 offers more benefits to manufacturers. For example, the manufacturers may earn **super-credits** for each vehicle sold with an emission of less than 50 g CO_2/km.

[46] Note: the CO_2-monitoring mechanism works with a so-called weight of the vehicle in 'running order', this includes in comparison to the 'empty weight' a driver (75 kg) and the fuel.

Since 2012, manufacturers have to pay a penalty for not keeping the target. Until 2018, the fee is different for an excess of the first (5 €/gCO_2), second (15 €/gCO_2), third (25 €/gCO_2) and for each subsequent gram (95 €/gCO_2). It is multiplied by the number of vehicles. [EC, Regulation No 443/2009, Article 4, 5, 9; EC, COM(2010) 656 final, p. 13] From 2019 onwards a homogenous fee of 95 €/gCO_2 has to be paid for each excess-gram. For example, a deviation of 10 gCO_2/km will account for a fee of 950 €. Assuming a life-cycle mileage of 250,000 km this accounts for a CO_2-price of 380 €/Mg which is much higher than the current CO_2-prices achieved in the ETS. 55 manufacturers out of 85, representing 98% of the registrations in the EU, achieved their specific emission targets for the year 2012. The average specific emissions of the new European fleet in 2012 is 132.2 gCO_2/km. The average mass of the fleet was 1,402 kg. [EEA, 2013, p. 3, 17] Ultimately, it took more than fifteen years from the initial initiative to a concrete legislative act, but it has to be noted that the expectations and lobbying were enormous:

> "[…] the legislative framework for implementing the average new car fleet target should ensure competitively neutral and socially equitable and sustainable reduction targets which are equitable to the diversity of the European automobile manufacturers and avoid any unjustified distortion of competition between automobile manufacturers. The legislative framework should be compatible with the overall objective of reaching the EU's Kyoto targets." [EC, COM(2007)856]

In 2012 the EC issued a regulatory proposal confirming a 95 gCO_2/km target for 2020 and specifying the regulatory details. [EC, COM(2012)393 final] After hard negotiations and strong lobbying activities, the new CO_2-target for cars was set to 95 gCO_2/km by 2021. The proposal strengthened the effect of the super credits, but also introduced a cap per manufacturer. An indicative target was set for post-2020 CO_2-emissions in the **range of 68-78 gCO_2/km for 2025**. It was endorsed by the European Parliament on 25.02.2014.[47] The different stakeholders are in a controversy about the costs for achieving the CO_2-fleet target. In 2007, ACEA stated that the average retail price of a new car will increase by 3.65 k€, if it has to meet the 120 gCO_2/km target. This figure was contested by many experts.[48] The International Council on Clean Transportation[49] put a figure of approximately 1 k€ for the additional manufacturing costs to meet the 95 g CO_2/km standard in 2020 relative to the baseline of 130 gCO_2 (and 2.2 k€ for a target of 70 gCO_2/km). [Mock, 2012, p. 30] A CO_2-reduction of 35 gCO_2/km equals a reduction in petrol consumption of 1.5 l/100 km, according to current prices, a pay-back would be achieved after 40 k-km. In reality, real car prices have been decreasing for several years in the EU despite the legislation on energy efficiency. [EC, 2011]

Finally, the EC managed to implement a mechanism which, in spite of all criticism on details, is working to make Europe's car fleet more efficient. It set a reliable, mid-term regulatory framework to encourage car makers to seriously develop more efficient drive trains. Also alternative technologies are supported through super credits and eco-innovations. However, fleet limits are not challenging enough by far, yet effective enough to promote zero CO_2-emission technologies such as BEVs or FCVs. All main European car makers achieved compliance already by 2012, without using the extra phase-in time. Real car prices even showed an under-proportionate growth compared to other transport related costs during the introduction phase, see *Figure 2-18* and the average car became more motorised, heavier and providing better comfort (see *Figure 2-14*). From these facts, it may be deduced that the

[47] http://ec.europa.eu/clima/news/articles/news_2014022501_en.htm, 04.04.2014

[48] http://www.euractiv.com/transport/carmakers-lash-eu-plans-co2-limits/article-162648, euractiv article of 28.05.2012

[49] Based on most recent data and assessment methodologies originally developed for the preparation for the United States 2017-2025 light duty vehicle regulation.

fleet limit could have been stricter without putting too much burden on manufacturers and consumers. This is particularly worse as the CO_2-targets cannot be reached with the current approach. It would be only possible if zero, or close to zero, CO_2-emission vehicles will make a significant impact. However, the 2021 targets can still be achieved without significant implementation of BEVs and ZEVs.

3.2.2 Regulation promoting hydrogen fuel and infrastructure development

The EC fuel quality regulation is targeted to set preconditions for the operation of exhaust gas control technologies and to directly reduce GHG-emissions. The following legislative acts could have a direct impact on the market introduction of H_2-fuel. **Directive 2003/17/EC** allows the Member States to require the exclusive marketing of clean fuels in ecologically or environmentally sensitive areas in order to protect human health and the environment. [EC, Directive 2003/17]

The **New Fuel Directive 2009/30/EC** is aimed at reducing the emission of key air pollutants and GHG released during the production and combustion of fuel between 2010 and 2020. It requires, among other aspects, a Low Carbon Fuel Standard and establishes **biofuels sustainability criteria**. These criteria rule out biofuels originating from primary forests, protected areas, highly biodiverse grasslands, wetlands and peatlands. By 2018, the use of biofuels has to achieve a life-cycle GHG-emission saving of up to 60%. This may promote the use of biogas from wind hydrogen[50].

The **Low Carbon Fuel Standard** requires to **reduce the fuel life cycle GHG-emissions** (CO_2, CH_4 and N_2O) per unit of energy from fuel and energy at all stages from extraction or cultivation to combustion including transport, distribution, processing and land-use changes **by 10% by 2020** (baseline of 2010). A gradual reduction of fuel GHG-emissions by 6% until 2020 with intermediate targets of 2% by 2014 and 4% by 2017 is required. A further 2% GHG-emission reduction has to be achieved by either supplying any other energy for transport, including electricity for vehicles or using GHG-reducing technologies (including CCS-technology). Another 2% reduction must be achieved from the purchase of credits through the Clean Development Mechanism under the Kyoto Protocol by 2020.

The Biokraftstoffquotengesetz (law on biofuel quota), 2007, amended in 2009, transposes Directive 2009/30 to the German law (§§ 37a - 37d of the Federal Immission Control Law (BImSchG) and § 50 of the Energy Tax Law (EnergieStG)). It set different biofuel quotas (relating to the energy content) for diesel and petrol fuel while abolishing the tax advantages of biofuels, see *Figure 3-2*. The quota may be fulfilled by blending biofuels to diesel or petrol, use of pure biofuel or of biogas. In 2015, the quota is replaced by a general GHG-reduction target. The law includes a penalty charge for non-compliance of 43 €/GJ for the petrol quota or 19 €/GJ for the diesel or overall quota. In practice, the market share of blended ethanol decreased to 1.4% in Germany in 2013 (see *Figure 3-3*).

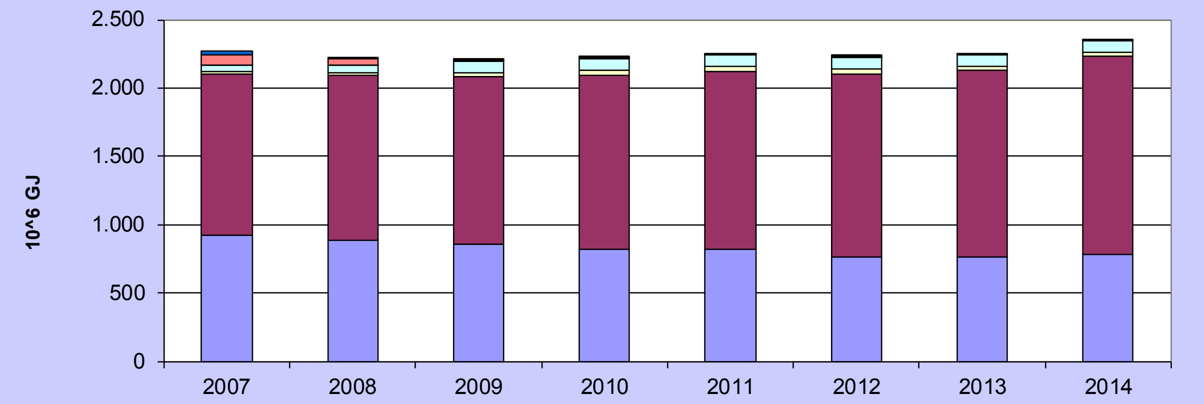
Year	Diesel quota	Petrol quota	Total bio-fuel quota
2007	4.4 cal.-%	1.2 cal.-%	
2008		2.0 cal.-%	
2009		2.8 cal.-%	6.25%
2015	Contribution to reduction of GHG-emissions:		3.0%
2017			4.5%
2020			7.0%

Figure 3-2: German biofuel quota

Directive 2009/28/EC on the promotion of the use of energy from renewable sources (RES) established a common framework for the promotion of renewable energy setting

50 **Wind H_2**: Wind electricity production is combined with H_2-production which is used as energy storage medium. Main elements are electrolyser, H_2-storage, FC, control unit. Wind performance prognosis and an optimised operating control allows a “planned CO_2-free power output”.

mandatory national targets (**consistent with a 20% Community target**) for the RES-share in gross final and transport energy consumption. For example, **the German RES-target for the gross final energy consumption is 18% for 2020**. In addition, each Member State has to ensure that the **RES-share in all forms of transport is at least 10% of the transport final energy consumption in 2020,** the share was only 5% in Germany in 2014. The Directive sets sustainability criteria for biofuels and a methodology to calculate GHG-emission savings (comparable to Directive 2009/30). [EC, Directive 2009/28, §1, Annex I]



	2007	2008	2009	2010	2011	2012	2013	2014
Petrol	40,8%	39,8%	39,0%	37,0%	36,4%	34,4%	34,1%	33,3%
Diesel	51,9%	54,2%	55,5%	57,2%	58,1%	59,9%	60,8%	61,7%
Blended bioethanol	0,5%	0,7%	1,1%	1,4%	1,5%	1,5%	1,4%	1,3%
Blended FAME	2,3%	2,7%	3,8%	3,8%	3,8%	3,9%	3,6%	3,6%
Bioethanol	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
FAME	3,1%	1,8%	0,4%	0,5%	0,2%	0,2%	0,0%	0,0%
Vegetable oil	1,4%	0,7%	0,2%	0,1%	0,0%	0,0%	0,0%	0,0%
Sum of biofuels	**7,3%**	**5,9%**	**5,5%**	**5,8%**	**5,5%**	**5,7%**	**5,1%**	**5,0%**

Figure 3-3: Development of fuel consumption in Germany in PJ[51]

By analogy with the **Californian Clean Fuels Outlet (CFO)** regulation to promote the development of alternative fuel infrastructure, the EC launched its **Clean Fuel Strategy**. The CFO is aimed at minimising the risk of all stakeholders to a manageable level. CFO triggers once k20 FCVs are deployed state-wide or k10 are deployed in an air cluster. It forces major refiners or importers of petrol (>M500 gallons) to establish clean fuel outlets depending on size and the number of ZEVs available with a reasonable dispersion and location of outlets. 32 H_2-stations shall be added by the CFO-approach. [CaFCP, 2012 (1), p. 18; CARB, no year]

The EC identified the lack of recharging and refuelling stations as one of three major obstacles for the market introduction of alternative fuels (the others are: high cost of vehicles and low level of consumer acceptance). In 2013, the EC proposed Directive (COM(2013)18) requiring Member States to adopt national policy frameworks for the market development of alternative fuels and setting binding targets for the build-up of alternative fuel infrastructure. Minimum infrastructure shall be provided (differentiated according to needs and technological maturity) for electricity, hydrogen and natural gas (CNG and LNG). In particular, the EC targets to build-up a network of publicly accessible refuelling points (maximum distance of 300 km) between the 14 Member States which currently are engaged in H_2-vehicles by 2020. [EC, COM(2013)18, 24.01.2013]

However, the contribution of the fuel sector to the EC's 20/20/20 targets is meagre. The share of biofuels is decreasing and the political will to put pressure on this item is vanishing

[51] Own depiction: Bundesamt für Wirtschaft und Ausfuhrkontrolle, Eschborn, table 9: Aufkommen zum Inlandsverbrauch an Otto-, Diesel- und Biokraftstoffen, http://www.bafa.de/bafa/de/energie/mineraloel_rohoel/amtliche_mineraloeldaten/2014/index.html

due to the sustainability discussion. The recent debate on concrete requirements for the installation of alternative fuel infrastructure will probably end in a stronger obligation for fuel suppliers. (The average price of an H_2-filling point is around 700 k€. The cost of adding CNG to an existing station for filling cars is about 300 k€, including compressor, storage and dispenser. The cost of an additional diesel or petrol dispenser is about 8-10k€, but costs are not comparable. The bulk of H_2- and CNG-filling station costs are determined by the compressor and dispenser as the main costs for a conventional filing station originate from sealing the surface area and the underground installation of tight tank systems as well as the related oil-water-separator facilities according to water management law.) The implementation of a German H_2-infrastructure covering k1 filling stations (for comparison: 919 CNG stations are currently available) would cost at least 700 M€. This sum would be easily manageable for the mineral oil industry in Germany and would be low in comparison with investments by the automobile industry in clean vehicles (also see section 6.2.2).

In conclusion, funding of filling stations became a transparent process in California. The procedure was already discussed between all stakeholders in the CaFCP, see section 4.1.2. The obligation to install further stations with a growing market provides certainty for car manufacturers to encourage them to invest in the continuous development of ZEVs. Thus, the predictability of developments by 2020 is much higher than in Germany, where the H_2-mobility initiative, see section 4.1.3, has changed the number of stations to be built several times and the mechanisms are unclear. In Germany, the funding procedure for infrastructure or vehicle implementation is still under discussion and is not at all transparent, yet. A compulsory linking of growing vehicle numbers and infrastructure expansion is missing. The EU is only currently discussing an approach to make Member states set targets for alternative infrastructure deployment.

3.3 Economic instruments

The European Commission decided in favour of a combined system of a carbon dioxide tax enforced and a cap and trade system. The **EU emissions trading system (EU ETS),** implemented by **Directive 2003/87/EC,** is a cornerstone of the EU's policy to combat climate change. EU ETS was the first - and is still by far the biggest - international system for trading GHG-allowances. Reports are available from EEA's ETS data viewer to the public.[52] The EU ETS sets a cap on the total amount of certain GHG-emissions. The cap is reduced over time so that total emissions are supposed to fall. Today, it covers more than k12 power stations and industrial plants in 31 countries as well as airlines.

During the ETS test phase (2005-2007), which was not designed to achieve major emission cuts, the Member States established National Allocation Plans (NAP) creating the total number of EU allowances (EUAs) and distributing them free of costs to individual plants. At the end of each year each site had to surrender sufficient EUAs to cover its CO_2-emissions. Each NAP had to be accepted by the EC. ETS was applied to energy-intensive industries, power plants and boilers over a certain size covering approximately 45% of the carbon emissions of EU15. During the first trading period the highest price for one EUA was reached in April 2006 (about 30 €/tCO_2). By the end of 2007, it became clear that the companies had a comfortable number of EUAs at their disposal and the price collapsed to 0.02 €/tCO_2. The EU shortened the number of allowances by nearly 7% below the EU15's 2005 emission levels for the second trading period (2008-2012) and extended the ETS to EU25. However, allowances were still distributed unequally between the sectors, clearly favouring the industry

52 http://ec.europa.eu/clima/policies/ets/index_en.htm; 26.02.2013

above the energy sector, because the European industry should not suffer under a competition disadvantage on international markets. At the end of 2007 EUAs for the second trading period were traded for about 22 €/tCO_2. In 2012, the verified emissions from all sectors were reduced by 13% in EU15 (to 1,421 GtCO_{2eq}) compared to 2005.[53]

Directive 2009/29/EC revised the ETS and set rules for Phase 3 (2013-2020) incorporating a **centralised EUA-allocation** with a linear decrease of the emissions cap of 1.74% p.a., even beyond 2020. NAPs no longer exists: the Commissioner for the Environment is the responsible authority. Auctioning shall progressively replace free allocation. Industrial installations receive allowances on the basis of product-specific benchmarks, but had to purchase at least 20% of their 2013 EUAs. This share shall rise to 70% in 2020 and 100% in 2027. Since Phase 3, ETS also covers new industries and new gases, e.g. N_2O. International offset credits will continue to be eligible for compliance under the EU ETS. Also, they might not account for more than 50% of reduction efforts between 2008 and 2020.[54] The EU sold M3.46 spot ETS EU carbon permits on EEX at 4.13 €/tCO_2 each on 25.02.2013. This EUA-price is much less than originally expected due to an over allocation of EUAs. (The German government expected about 17 €/tCO_2 revenue per permit.[55]) A recovery of the market to attract low carbon investments would need the 'back loading' of about M900 EUAs. In 2013 (2014), the price fluctuated between 2.93 to 4.94 €/MgCO_2 (4.17 to 7.10 €/MgCO_2) at ICE, London, (see Figure 3-4).

Figure 3-4: Prices for EUA in the second trading period[56]

Road transport is not yet covered under the ETS. A cap-and-trade system for fuel suppliers or a baseline-and-credit system for car manufacturers were discussed. The Commission indicated the enclosure of road transport into the review of the ETS after 2013. [EC, COM(2006)676, 2006, §3.1] The UK's Department of Transport proposed a baseline-and-credit system related to the emission intensity of new cars to the EC's Motor Vehicle Emission Group as far back as 1992. The principle was to provide each new car free of charge with CO_2-emission credits corresponding to the average permissible specific emission in that particular year. For cars achieving a better fuel efficiency than required, manufacturers would be free to sell their surplus credits to those who did not meet the standard. To prevent manufacturers from withholding credits from sale to competitors, part of the credits would be reserved for an EU authority, which would auction them and return the revenue to the original owners. [T&E, 2005, p. 30]

53 http://www.eea.europa.eu/data-and-maps/data/data-viewers/emissions-trading-viewer, 26.02.2013

54 http://www.ieta.org/index.php?option=com_content&view=article&id=324:the-eu-emission, 26.02.2013

55 http://www.unendlich-viel-energie.de/media/file/88.AEE_RenewsKompakt_Emissionshandel_Energiewende_jun13.pdf, 08.11.2015

56 Own depiction: http://www.eex.com/en/market-data/emission-allowances/auction-market/european-emission-allowances-auction/european-emission-allowances-auction-download; 25.07.2015

All Member States apply a number of **fiscal measures on the use of vehicles**. Stand-alone measures are not linked to specific standards, e.g. VAT and insurance tax. Others, like the registration fee and the fee for obtaining the driving license are aimed to cover the costs for the particular administrational service.

The **tax on car ownership or circulation tax** is a targeted tax to contribute to the infrastructure costs. The tax is based on the vehicle age, power, fuel type and fuel consumption, environmental performance and weight. In Germany, a CO_2-emission based circulation tax is charged at 2 € for each excess gram of CO_2/km above 120 gCO_2/km. In addition, the tax is raised according to each opened 100 ccm³ of capacity: 2 €/100 ccm³ for a petrol fuelled and 9.50 €/100 ccm³ for a diesel fuelled car. BEVs and FCVs first registered between 18.05.2011 and 31.12.2015 are exempt from circulation tax for a period of ten years.[57]

Registration taxes are normally due with the first registration of a vehicle. Each year, more than M13 new passenger cars are registered in the EU, while over M3 cars are moved to another Member State.[58] In the Member States, the tax rates differ widely and are charged by reference to the value, the power, the environmental performance, the vehicle fuel consumption or combinations of the factors. Germany and some other Member States do not have any registration tax. France introduced different rates for various carbon classes from 136 to above 200 gCO_2/km from 0.1-6.0 k€. Denmark has, by far, the highest tax: the rate is 105% up to a value of 15.5 kDKK (2.08 k€) and 180% of the remainder. [ACEA, 2013, p. 2] In 2005, the Commission suggested harmonising the taxation of passenger cars to avoid internal market fragmentation. It was planned to gradually abolish the registration tax and to link at least 25% of the total tax revenue from annual circulation taxes to CO_2-emissions (by the start of the Kyoto period in 2008; at least 50% by 2010). CO_2-emissions should be reduced by 4 to 8.5% (4.9% in Germany). [EC, COM(2005)261, p. 7-8] The proposal was not accepted.

The **taxation of fuels** is regulated in **Directive 2003/96/EC**. It set minimum rates, see *Figure 3-5*, on all energy products when used as fuel or for heating purposes. Nevertheless, the Member States may set higher fuel taxes based on the sulphur content, the octane number or the biofuel share. [EC, DG Taxation and Customs Union, 2008, p. 8-10] Most Member States are substantially promoting the use of diesel and the implementation of alternative fuels via fuel tax reduction. Today, the UK is the only Member State applying the same fuel tax to petrol and diesel, at least on a litre-basis. Directive 2003/96/EC permits EU Member States **to exempt fuels from renewable sources from up to 100% mineral oil duties** (Article 15). This ruling applies both to pure fuels and pro rata to the mixing of biogenic components.

The Commission proposed (**COM/2011/169**) to amend Directive 2003/96/EC to align energy taxation to the 20/20/20 targets and to remove current imbalances in the EU. It is proposed to split the energy tax into two components, taking into account both CO_2-emissions and energy content of a product (*Figure 3-5*). It covers all consumers of motor and heating fuels who are not subject to the EU ETS. The proposal set the *minimum CO_2-taxation rate* at 20 €/tCO_2 for all uses of the energy products. This value corresponded with the expected future price for CO_2-emissions in the existing EU ETS. In addition, the energy consumption taxation is 9.6 €/GJ on the basis of the net calorific value of the energy products and electricity to be achieved gradually by 2018. This is the same energy related tax rate as for petrol according to the current Directive. The rate for energy products used as motor fuel for certain purposes (Article 8(2)) and for electricity (Annex I) is set to 0.15 €/GJ. Nonetheless, Article 15 shall sustain and would allow Member States to exempt or reduce the level of taxation for fuels

57 http://www.bundesfinanzministerium.de/SiteGlobals/Functions/KfzRechner/cartax.html, 15.11.2015
58 http://europa.eu/rapid/press-release_IP-12-1368_en.htm, 14.04.2013

from renewable energy sources, for electricity from biomass or from FCs, for public transport fuels etc. [EC, COM(2011)169, 2011] Due to the calculation scheme the total minimum energy tax increases only slightly for petrol, less than 19% for diesel, but more than 300% for LPG and natural gas. The ECs energy tax proposal is highly controversial and not yet agreed. The income from the excise duty on fuel for the budget is significant. For example, Germany made 40 G€ in 2014. [BMF, 2015]

Energy product	Net cal. value in GJ/t	Density kg/m³	GJ/ Unit	t CO_2/ TJ	t CO_2/ Unit	CO_2-Tax min.€	Energy tax in €	Minima propos. by 2018	Current minima €/Unit	Current minima €/GJ	In-crease	Unit
Petrol	44.0	745	32.8	69.2	2.3/	45.4	315	360	359	11.3	**0.3%**	*/1,000 l*
Gas oil	42.3	832	35.2	74.0	2.6/	52.1	338	390	330	9.4	**18.2%**	*/1,000 l*
LPG	46.0			63.0	2.9/	58.0	442	500	125	2.7	**300.0%**	*/1,000 kg*
Natural gas	47.2			56.1	1.1/	1.1	9.6	10.7	2.6	2.6	**311.5%**	*/GJ*

Figure 3-5: Current and proposed tax rate (use as propellant, minimum rates)

The absolute value of the energy tax is decreasing; also its share on the total German tax volume declined from 10% in 2002/2003 to just 6% in 2014, see *Figure 3-6*. However, it does not seem possible for the State to abstain permanently from this significant tax income to promote alternative fuels. Fuels which have reached a significant market share will need to be taxed. In Germany, the energy tax is a fixed rate which was increased in five steps from 1999 to 2003, e.g. for petrol from 50.1 to 65.45 ct/l. The diesel energy tax is 47.04 ct/l. The German tax system partly compensates this difference through higher circulation taxes on diesel cars. Natural gas (13.90 €/MWh) and LPG (0.18032 €/kg) are subject to a reduced tax (18-19% of the petrol rate) until 31.12.2018. However, the 2013 coalition agreement calls for a prolongation of this tax exemption.

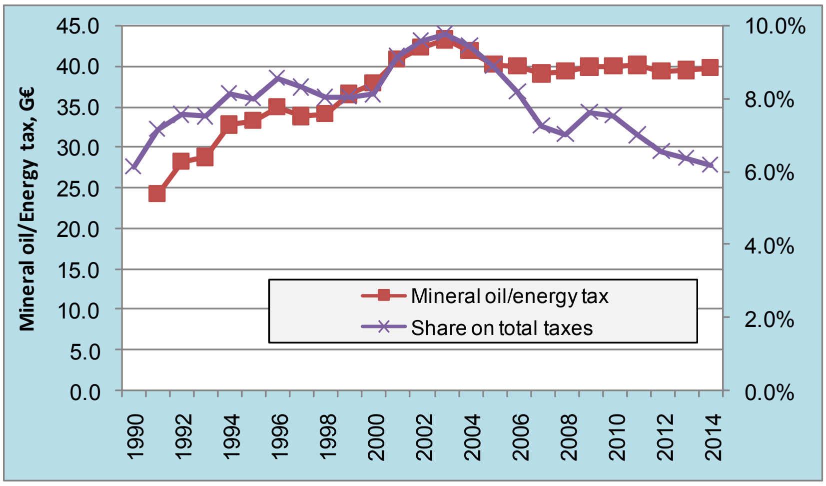


Figure 3-6: Proportion of the energy tax on total state tax revenue in Germany [BMF, 2015]

Germany exempted pure biogenic fuels from mineral oil duties as early as the 1990s. Since 2007 biodiesel and vegetable oil blends are fully taxed (see *Figure 3-2*). Pure biodiesel and vegetable tax rates have been increased gradually from 2006 until 2015. [BMF, 2008, p. 83-85] Currently no fuel tax is applied to **hydrogen**. The German **Renewable Energy Sources Act**, 2012, includes any synthetic gas, (e.g. methane produced from renewable hydrogen) which is produced as a storage gas (§3, Nr. 9). Network operators are forced to give priority to the connection of such energy production facilities within their network and the electricity produced has to be transmitted and distributed preferentially. [Deutscher Bundestag, EEG, 30.06.2011]

However, the incentive effect of the German fuel taxation is inconsistent. By 2015, biodiesel, a renewable fuel which reduces CO_2 by 20-75% depending on the TtW process, is taxed at 13.79 €/GJ (fossil diesel with 13.36 €/GJ). Bioethanol, with a TtW CO_2-reduction potential of

10-70% is taxed at 2.17 €/GJ, even if competition with food might be even higher and CO_2-reduction potential less. LPG is another example, the Zafira Tourer LPG 1.4 ecoFLEX emits 139 gCO_2/km when using LPG, the Zafira Tourer 1.6 CNG Turbo ecoFLEX emits 129 gCO_2/km, the Zafira Tourer 1.6 SIDI Turbo154 gCO_2/km. Thus, the CO_2-emission benefit is less than 15%, but the tax benefit is more than 75%. In addition, the steering effect towards vehicles consuming less of the German fuel tax is low. [kba, 2012] The European-wide introduction of any clean fuel would require better harmonisation of CO_2-related tax rates. Nevertheless, it might be more efficient to integrate motor fuels into the ETS.

Road charging is applied in some Member States to cover infrastructure costs. It is charged as a fixed amount, e.g. per crossing of a bridge or passing through a tunnel (user charge), as a function of the distance travelled (toll) or as a periodic payment, e.g. 'vignette system'. European legislation on road charging concentrates on HDVs (above 3.5 tonnes). The extension of the toll system to LDVs and cars is regularly debated, but with no results for Germany, yet. Road charging could be related to the emissions of the vehicles.

Directive **2009/33/EG** on the promotion of clean and energy-efficient road transport vehicles, requires contracting public bodies and operators to take into account operational lifetime energy and environmental impact when purchasing road vehicles. Emission costs shall be charged as follows: CO_2 (3-4 €/kg), NO_x (0.44 €/kg), NMHC (0.1 €/kg) and particulate matter (8.70 €/kg). The Directive was transferred to German Law by the **Verordnung über die Vergabe öffentlicher Aufträge** (Vergabeverordnung – VgV, 2011). The respective data for cars is available from official sources (kba-statistics).

The second German stimulus package is another example for the direct support to the procurement of cleaner cars. It included a 2.5 k€ bonus to two million consumers to trade-in inefficient vehicles. Further incentives and loans were put in place to promote sales of fuel efficient cars and the development of low carbon engines. [IEA, 2009 (1), p. 2-5, 7] Also Norway is demonstrating how large subsidies and very attractive incentives could support alternative vehicle market introduction. For three months at the end of 2013, the BEVs Tesla Model S and the Nissan Leaf were the best-selling models among all cars sold in the country (about k1.2 BEVs/month). k21 BEVs have been registered in Norway (M5 inhabitants) in 2014. BEVs are not just exempt from purchase tax and VAT, but pay no road and ferry tolls or parking fees; they cost less to insure and can be charged up using free electricity from thousands of points. Local government also subsidise the installation of charging points in homes.[59] In the case of a Tesla this equates up to a 70 k€ subsidy. In addition, bus lanes could be used by BEVs. The overwhelming success of the programme has led to a domination of BEVs on bus lanes and a discussion on supporting clean (luxury or second) cars instead of public transport. In any case, the real attractiveness of BEVs will have to sparkle if subsidies stop after co-financing k50 BEVs or in 2018.

3.4 Standardisation of fuel cell (electric) vehicles and fuelling equipment

In a globalised market place standards play a crucial role in overcoming technical barriers to trade and to comply with national or regional requirements. Standards ensure a certain product quality, i.e. conformity with "universal" consumer requirements allowing for a larger export market. Standards help to ensure the free movement of goods within the internal market and allow European enterprises to become more competitive. Standards likewise help protect the health and safety of consumers and contribute to environmental protection.

[59] http://www.theguardian.com/environment/2014/jan/29/norway-electric-cars-sale, 07.02.2014

Standards support the development of innovative products as market participants may concentrate and use R&D means on the basis of standards and exclude variants with no good prospects.[60] The more diverse the set of technology related variations, the more expensive and challenging it is to sell different equipment worldwide. Ultimately, this results in higher prices for equipment suppliers and consumers and takes longer for products to be modified for different markets. Some markets may be fully omitted because the standards are too different from other markets or are too complex to be fulfilled with regard to the size and the potential of the respective market. For example, high-pressure cylinders, which are manufactured according to different standards and are tested according to different requirements by various local authorities, become more expensive. [Harris, 2004, p. 4]

Norms and standards have an essential meaning for the process of market penetration of FCVs and for the consumer acceptance of handling hydrogen. The H_2FCV-market entry process is carried by international organisations and industries which started early to coordinate the various stakeholders involved and to develop norms and standards for FCVs. Thus, the level of standardisation is quite high, e.g. compared to the electro mobility industry. **Hydrogen/Fuel Cell Codes & Standards** homepages give an overview of available norms and standards**.**[61] The most important standards are summarised in Annex 8.1.

Within the different standardisation organisations several working groups exist for the development of hydrogen related standards, e.g. **CEN/BTWG 149** "Liquid and Alternative Gaseous Fuels" to harmonise European fuel standards or **ISO/TC 197 Technical Committee**, **Hydrogen technologies**. In the absence of H_2-standards, respective NG standards are used in an adjusted variant. The US **Society of Automotive Engineers** (SAE), in particular the **Fuel Cell Standards Committee,** has published specific H_2FC-technology standards. They are applicable indirectly for FCVs homologated in Europe as FCVs are usually developed for an international market. SAE standards are intended to recommend design and construction, operation, emergency response and maintenance practices for the safe use of FCVs by the general public. In particular, the standards on filling stations are used as a reference in Europe. Also, the Canadian Standards Association (CSA Group) develops H_2FC-related standards (**HGV- Hydrogen Gas Vehicles**) which are also applicable in the US.

H_2FCV-technology standardisation started early and the necessary standards for market development, most importantly H_2-quality and FCV-filling procedures, are in place. Their technical and economic feasibility is currently being tested in demonstration projects. The further development of standards will take place in parallel with the technology development. Standards are being elaborated jointly for the European and Northern American market; this supports market entry in these key markets.

3.5 Global population development and economic growth

The demographic development is one of the essential variables of future energy consumption patterns. According to the medium variant of UN scenarios the world population is projected to surpass G9 people by 2050 and exceed G10 in 2100. This increase will occur mostly in the less developed regions, whose population is projected to rise from G5.7 in 2011 to G8 in 2050 and G8.8 in 2100. The population of the more developed regions is expected to change little from G1.24 in 2011 to G1.34 in 2050 and would have declined were it not for

60 http://europa.eu/legislation_summaries/internal_market/single_market_for_goods/technical_harmonisation/l21001c_en.htm, 25.02.2013

61 http://www.fuelcellstandards.com/vehicle_apps.html, http://www.fuelcellstandards.com/hydrogenapps.html, 25.02.2013

the projected net migration from developing to developed countries, which is expected to average annually M2.2. [UN DESA, 2007, p. vii, 1; 2011, p. xiii]

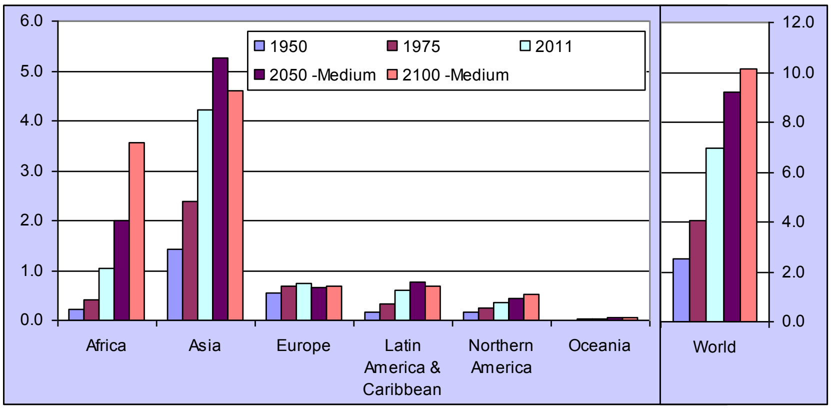


Figure 3-7: Development of world population in million 1950-2050, UN medium variant [UN DESA 2011, p. 2]

The population in H_2FCV-key markets will not increase significantly by 2050. However, the world's urban population will continue to grow faster than the total population. The process of urbanisation is advanced in the more developed regions where already 75% of people lived in urban areas in 2005, a proportion that is expected to increase to 81% in 2030. By contrast, the population of developing countries living in urban areas will increase from 43% to 57% from 2005 to 2030. This rapid urbanisation trend creates major challenges in terms of transport, housing, air pollution, water supply, sanitation and infrastructure development. [UN DESA, 2005, p. 9]

Economic growth is defined as the quantitative change or expansion in a country's economy. Economic growth is conventionally measured as the percentage increase in Gross Domestic Product[62] (GDP) or Gross National Product (GNP) during one year. Continuous growth is seen as the benchmark for any successful economic policy. It is one of the fundamental key figures reported by every nation to the International Monetary Fund. The evaluation of the GDP needs to consider the absolute growth, the per capita growth as well as developments of the past. For example, German GDP has increased continuously, except during the 2008 recession, by an average of 47 G€/a. [Institut für Wachstumsstudien, 2008]

Price Waterhouse Cooper analysed the GDP development of all G20 and the seven largest emerging countries (E7)[63] until 2050. GDP is measured in Purchasing Power Parity (PPP) terms, which adjusts for price level differences across countries. The sum of GDP in PPP terms of the E7 seem to be bigger than that of the G7 in 2020. Calculating in market exchange rate terms (MER) this catching-up process takes longer. In any case, this process results in a growing middle class and an increasing consumer market in E7 countries. [PwC, 2011, p. 3] By 2050, six of the eight largest economies are from E7 countries (except of Turkey) mainly due to the significant increase in population. The US still has the largest GDP/capita, but the gap is closing. In 2009, the Chinese GDP/capita made just 15% of the US, in 2050 it will be nearly half. The H_2FCV-key markets (EU, US, Canada, perhaps China) continue to hold economic leadership positions. However, the example of NGVs has shown (see section 4.2.2) that the penetration of markets in emerging economies is possible, if the transport sector could be supplied with local resources instead of imported oil. In the case of strongly decreasing H_2FC- and electrolyser prices, H_2FCVs could be used at these markets to produce cheap hydrogen with local resources, perhaps stored on-board at lower pressures.

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62 The GDP describes the value of all final goods and services produced in a country in one year (added value). GNP is GDP plus income that residents have received from abroad, minus income claimed by non-residents. [http://www.worldbank.org/depweb/english/beyond/global/glossary.html; 25.02.2013]

6363 Brazil, China, India, Indonesia, Mexico, Russia, Turkey

3.6 Energy security and the price of fuel

Energy security is a state of affairs characterised by conditions and policies that safeguard the economy against circumstances threatening significant short or long-term increases in energy costs. [Parry et.al., 2003, p. 1] It is a concept with many dimensions, one of which is the oil dependency. **Oil dependency** is not simply a matter of the volume of oil imports. It is a combination of the vulnerability of the economy to higher oil prices and oil shortages and a concentration of world oil supplies in a small group of oil producing states that are willing and able to use their market power to influence oil prices. The **Organization of Petroleum Exporting Countries (OPEC)** plays[64] a crucial role for the pricing of crude oil. OPEC members are willing to produce well below their capacity in order to retain influence over prices, to secure a steady income to its members or to increase the oil output to allot alternative fuels a more expensive and unattractive position. [OPEC, 2007, introduction] In 2012, OPEC made 43% of world crude oil production. It has 73% of the proven reserves.[65] The **vulnerability** depends on the volume of oil consumption, the availability of economic oil substitutes and the level of oil imports. [Greene et.al. 2005, p.1] The transport sector is particularly vulnerable due to its high dependence on oil. Political, social and religious conflicts between the oil producing, transferring or consuming countries complicate the situation. For example, Europe's oil security depends heavily on Russia's oil pipeline network as Russia is Europe's main oil importer (share of 30% in 2013).[66] Neighbouring countries, which are involved through the pipelines normally receive a percentage to pay for the transfer, but Russia and Ukraine, in particular, are in conflict. In addition, the level of oil dependency is influenced by geopolitical actions, e.g. efforts to stabilise oil-exporting regimes (recent examples include Libya, Kuwait, Saudi-Arabia, Iraq) as well as geological or technological issues, e.g. R&D investments to expand domestic fuel reserves.

The world's **recoverable conventional oil reserves** are estimated to be 1,532 Gbbl (01.01.2012). This stock of proved crude oil reserves are those quantities of petroleum which, by analysis of geological and engineering data, can be estimated with a high degree of confidence to be commercially recoverable from a given date forward. The largest reserves are located in Saudi Arabia, followed by Venezuela and Canada.[67] At a current crude oil consumption rate of 32.5 Gbbl/a (2012) **this would last for about 47 year,** i.e. the year 2059. About 1,075 Gbbl were removed in 150 years of production as of 2008.[68] Of the 65 largest oil producing countries in the world, up to 54 have passed their peak of production, including the USA (1970), Indonesia (1997), Australia (2000), the UK (1999), Norway (2001) and Mexico (2004).[69] The IEA recently assessed more than 800 oil fields in detail, covering three quarters of global reserves, showing that most of the biggest fields have already peaked. The IEA chief economist predicted peak oil will happen by 2019.[70] However, in 2012, world oil production still increased by 1.9 Mbbl/d, also caused by the heavy use of unconventional oil.

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64 OPEC is a permanent, intergovernmental organisation established in Baghdad in 1960.

65 http://www.bp.com, Statistical Review 2013, table: statistical_review_of_world_energy_2013_workbook.xlsx, 28.02.2014

66 http://ec.europa.eu/energy/observatory/oil/import_export_en.htm; 06.07.2014

67 https://www.cia.gov/library/publications/the-world-factbook/rankorder/2178rank.html; https://www.cia.gov, World Factbook, tables: "Field Listing : crude oil - proved reserves", "Crude Oil – Production", 20.02.2013

68 http://www.eia.gov/forecasts/steo/report/global_oil.cfm, 28.06.2013

69 http://www.energybulletin.net/primer.php, 22.02.2013

70 http://www.independent.co.uk/news/science/warning-oil-supplies-are-running-out-fast-1766585.html, 23.02.2013

However, the more significant question than 'When will oil peak?' may be: What will the future rate of decline in oil production be? Some form of co-ordinated adaptation might be possible if the annual drop in available oil is less than 1-2%, whereas 10% or more would disturb the global economy heavily. The IEA predicts a long plateau and a very modest global decline rate. Most models project decline rates between 2-4%. Thus, peak oil does not mean running out of oil. However, the most accessible oil resources were extracted first. This oil was on land, near the surface, under pressure, light and sweet and thus easy to refine. The remaining oil is more likely to be off-shore, far from markets, in smaller fields and of lesser quality. Therefore, peak oil indicates the end of cheap oil, easily accessible and relatively homogenous oil rather than the end of oil.[71] Nonetheless, oil is a finite resource.

The importance of the unconventional resources is growing. **Conventional oil** includes crude oil, natural gas liquids and condensate liquids, which are extracted from natural gas production. **Unconventional oil** consists of a wider variety of liquid sources, including oil sands, extra heavy oil, gas to liquids and other liquids. In general, it is heavier, carrying more carbon and more impurities. The extra-heavy, impure oils require very large energy inputs to upgrade and pre-process them into synthetic crude oil that is then processed by a refinery. Some new oils are effectively solid and must be removed through mining or heating up in situ until they flow. [U.S. Congress, 2005, pp. 2] Proven reserves of unconventional oil are around 400 Gbbl, with estimated recoverable resources of 3,200 Gbbl. [IEA, 2014, p. 18] It is currently not clear, which part of this would be economically, technically and sociably acceptable to deploy under future conditions. The categories “conventional” and “unconventional” do not remain fixed and, over time, as economic and technological conditions evolve, resources hitherto considered unconventional can migrate into the conventional category. [http://www.iea.org/aboutus/faqs/oil/, 14.02.2013]

Unconventional oil becomes particularly important as it is also located outside the OPEC countries and diversifies oil production in geographic, geological, chemical and economic terms. For example, the IEA forecasts that the growing supplies of crude oil extracted through new technologies, including hydraulic fracturing of underground rock formations, will transform the US into the largest producer for about five years starting around 2020. Already in the first half of 2012, the US met 83% of its energy needs from its own resources.[72]

The **fuel price** is influenced by various parameters. In Germany, the fuel price includes the price of the product, including influences of the **USD-Euro-exchange rate**, excise duty on fuel, VAT, additional fuel cost components such as margin of the mineral oil companies and subscription to the German Oil Storage Association. The **price of crude oil** is determined by international markets. *Figure 3-8* depicts the price development of crude oil since 1947. Since the year 2000 the oil price is increasing. On 2nd of January 2008 the oil price firstly broke the 100 USD/bbl mark. Dated Brent averaged 98,94 USD/bbl in 2014.[73]

The cost of crude oil as traded on the stock market does not reflect actual production costs which consist of the finding and lifting costs. Finding costs cover oil and natural gas exploration as well as production development costs, including costs for purchasing properties that might contain reserves. The direct lifting or production costs cover the costs of operating and maintaining wells, related equipment and facilities. Total lifting costs also include production taxes. Because oil and natural gas are often produced together separate costs for each are

71 http://www.energybulletin.net/primer.php, 22.02.2013
72 http://www.bloomberg.com/news/2012-11-12/u-s-to-overtake-saudi-arabia-s-oil-production-by-2020-iea-says.html, 14.02.2013
73 http://www.indexmundi.com/commodities/?commodity=crude-oil-brent&months=60; 03.07.2015

not available. The EIA regularly compiles a report on worldwide US energy company operations showing finding and lifting costs in different regions of the world. The sum of lifting and development costs in the low-cost producing areas of the Middle East was less than 20 USD/boe in the period of 2004-2009. [EIA, 2007, pp. 20-24; http://www.eia.gov/tools/faqs/-faq.cfm?id=367&t=6, 14.02.2013] However, US upstream oil and gas spending has been increasing rapidly with the onset of the so-called “shale” or “unconventional revolution”. US upstream finding costs (excluding spending on the acquisition of proved reserves) increased by an average of 13% p.a. and lifting costs rose by an average of 10% p.a. between 2004 and 2013. Full-cycle costs have averaged over 60 USD/boe between 2008 and 2013. The difference between these competitive costs and the market price is paid as a wealth transfer by the consuming countries to the producing countries. The EU imported 3.65 Gbbl in 2014 paying 360 GUSD.[74] [EY, 2014]

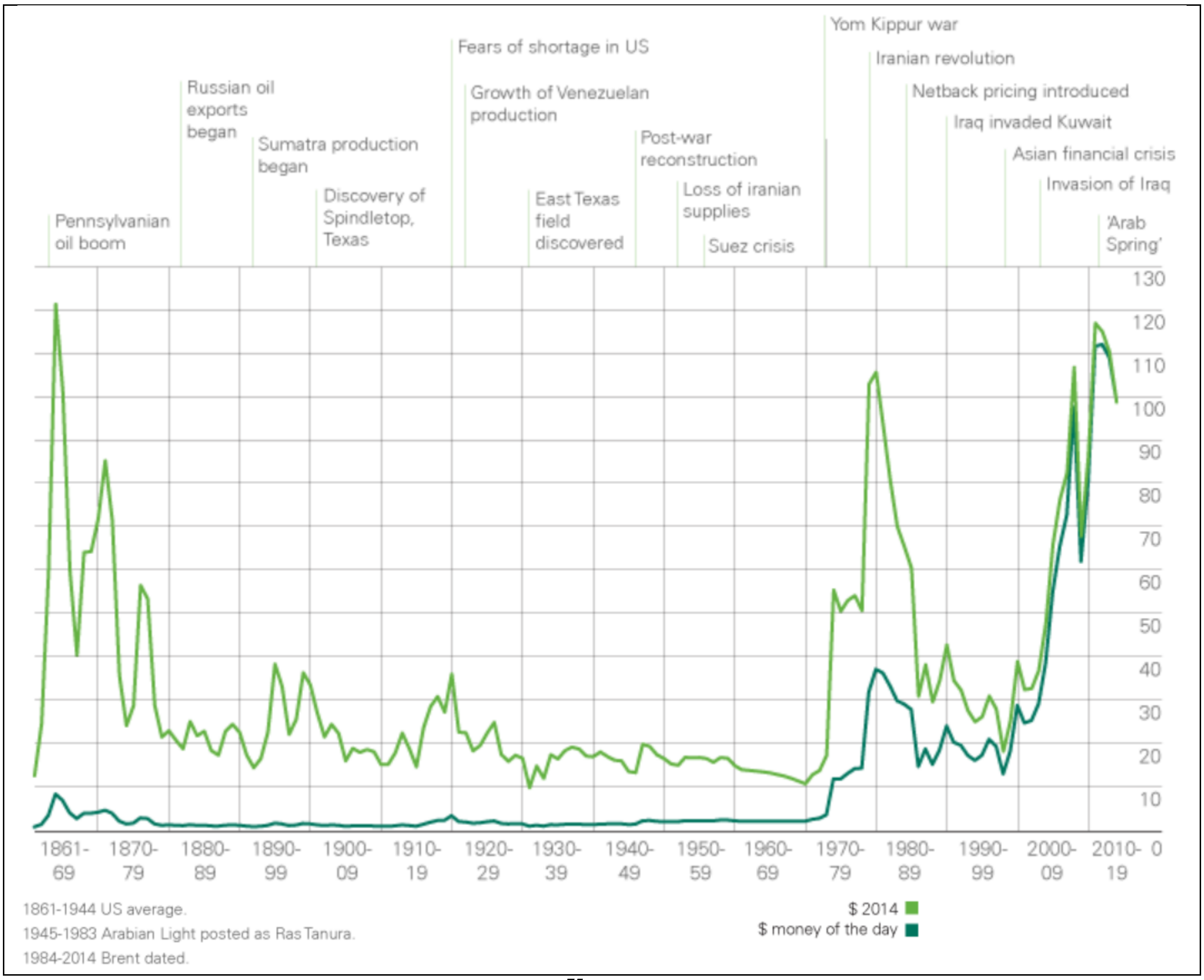

Figure 3-8: Development of crude oil price[75]

However, the true price for crude oil also includes the livelihoods of communities in oil-producing regions that have lost access to clean water and productive land. It also includes authoritarian regimes that use the oil revenues to maintain repressive states as well as oil wars and low-intensity conflicts.

74 https://ec.europa.eu/energy/en/statistics/eu-crude-oil-imports, 15.11.2015

75 http://www.bp.com/en/global/corporate/about-bp/energy-economics/statistical-review-of-world-energy/review-by-energy-type/oil/oil-prices.html, 04.07.2015]

Finally, the fuel costs also depend on transport and refinery costs. A barrel of crude oil can be "cracked" into a number of different products from heating oil, petrol to kerosene. The share of product output depends on the available refinery technology and the quality of the crude oil. Light oils allow for higher yields of light derivates such as petrol and kerosene as heavy oils producing heavier fuel oil and bitumen. Modern refineries could increase the diesel share to 40% of all final products. [Kroher, 2009. p. 22-25]

The IEA Reference Scenario assumes quite moderate increases of oil prices with rising demand and supply costs. In nominal terms[76], prices approach 102 USD/bbl by 2015, 131 USD/bbl by 2020 and almost 190 USD/bbl by 2030.[77] The oil price forecast includes gradually tightening international oil markets, a steadily recovering world economy and - in the longer term - rising marginal costs of supply together with demand growth in non-OECD countries. In the IEA 450-ppm-Scenario, oil prices are assumed to follow the same upward trajectory as in the Reference Scenario to 2015 and then remain flat to 2030, due to a weaker demand and the absence of a need to produce oil from costly fields. The oil price is assumed to plateau at 90 USD/bbl in real terms[78] in 2020. Final prices also take into account carbon prices under cap-and-trade systems that are assumed to be introduced in many parts of the world in this scenario. The **carbon price** in the OECD countries is predicted to reach 50 USD/tCO_2 in 2020 (which increases the cost of oil by 21 USD/bbl) and 110 USD/tCO_2 in 2030 (which increases the cost of oil by 46 USD/bbl). [IEA, 2009 (2), p. 4-6]

The EC's RS_{2013} set key assumptions, e.g. on reserves notably of shale gas and other unconventional hydrocarbons, on world economic developments, on carbon prices (reflecting the Copenhagen-Cancun pledges) and on dedicated policy measures. Additional climate policies are assumed only for the EU for the period beyond 2030. Up to 2035, the projections result in oil prices which are broadly in agreement with the IEA forecasts. For the shorter term, higher prices reflect failure of productive capacity to grow in line with demand (due to global economic growth). The situation eases somewhat around 2020. RS_{2013} uses a **carbon price** of 10 €/tCO_2 in 2020 and of 35 €/tCO_2 in 2030, which is more than twice times less than the value of the IEA-450-ppm scenario. In 2050, RS_{2013} assumes a price of even 100 €/tCO_2. Any volatility in the carbon price will lead to high uncertainty for investors in the power sector, thus significantly influencing the direction of investments to conventional or new energy sources.

76 Prices in nominal terms reflect the absolute prices in the year given.

77 In the scenarios, the IEA uses an average real term crude oil import price as a proxy for international prices. It has been around 3 USD/bbl less than WTI in 2008 and is assumed to reach 87 USD/bbl in 2015, 100 USD/bbl by 2020 and 115 USD/bbl by 2030 (in year-2008 USD).

78 Prices in real terms reflect the same value in the future as today.

4 Research, development and deployment perspective

Hydrogen FCV-technology is currently demonstrated in real market settings. Vehicle manufacturers such as Daimler, Toyota or Hyundai have transferred vehicles to regular customers since several years. Daimler started to lease a small H_2FCV-series to customers. In this development phase the two-way feedback between market experience and research is especially important for the further technology improvement. H_2FC-technology deployment is driven by large research initiatives and strategic hydrogen projects as well as electrical vehicle technologies and infrastructure development.

4.1 Overview on basic research initiatives and strategic hydrogen projects

There are several private and public organisations which are expediting the market introduction of hydrogen fuel, either by provision of information or by financing and implementing of research and demonstration. Some of these activities had, or still have, the strength, capacity or quality to directly impact on current market development. International projects with a more general background are listed in Figure 4-2. Details are available at the respective project websites.

Hydrogen Implementing Agreement (HIA), 1977 [http://ieahia.org/] and **Implementing Agreement for a Programme of Research, Development and Demonstration (R&DD) on Advanced Fuel Cells, 1990** [http://www.ieafuelcell.com/] of the International Energy Agency (IEA). HIA is targeted on collaborative H_2-R&D and information exchange among member countries in particular on H_2-production. The vision of the HIA is for a hydrogen future, based on clean sustainable energy supply of global proportions that plays a key role in all sectors of the economy.[79] The 2009-2014 HIA R&DD work programme on Advanced Fuel Cells included aspects of cell and stack cost and performance, endurance, materials, modelling, test procedures and minimisation of stack size.

The foundation of the **International Partnership for the Hydrogen and Fuel Cells in the Economy (IPHE)** was facilitated by the US Departments of Energy and of Transportation in 2003 to accelerate the transition to a hydrogen economy between 17 partners, incl. international co-operation, common codes and standards and information sharing on infrastructure development. [http://www.iphe.net/]

The **European Framework Programmes (FP)** (1984-2013) supported manifold Research and Technological Development (RTD) projects in the EU. The relevance expressed in budget figures of the scientific areas changed significantly during the course of the programme. The First Framework Programme **FP1** (1984-1987) had a budget of only 3.271 GECU. **FP5** (1998-2002, budget of 14.96 G€) emphasised hydrogen in Key Action 4 on ‘Energy, environment and sustainable development’ (2.125 G€). It targeted at the optimisation of transport combustion with cleaner hydrocarbon and alternative fuels, including on-board H_2-reforming. RTD on FC-technology was aimed at achieving a comparable or lower cost than for conventional technologies, but with substantially lower

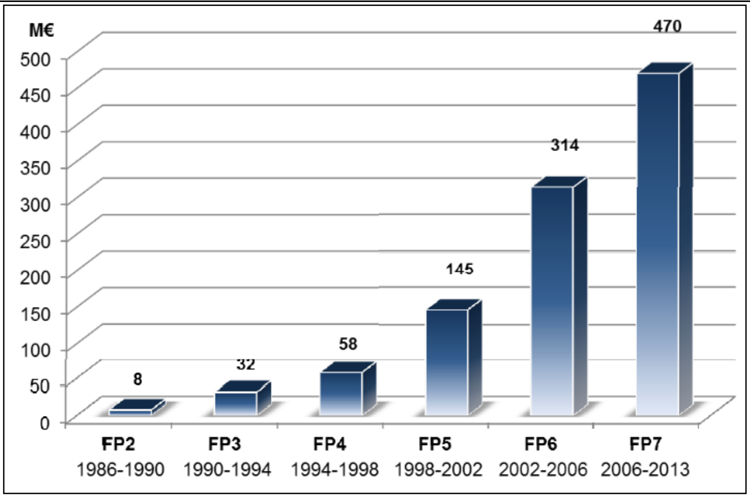

Figure 4-1: EC funds to H_2FC-research in the FPs [Cerri, 2011 p. 13]

79 http://ieahia.org/About-IEA-HIA.aspx, 15.11.2105

CO_2- and pollutant emissions. The use of hydrogen fuel became an important research topic within **FP6** (2002-2006, budget of 17.5 G€). [EC, 2004]. [80]

FP6 concentrated on large-scale urban fleet demonstration, priority was given to captive fleets like hybrid FC-buses, e.g. the **CUTE/ECTOS/STEP** projects examined 33 DaimlerChrysler FC Citaro buses and a range of different H_2-production and refuelling solutions in eleven cities around the world, including Hamburg and Stuttgart (CUTE, 2003-2006, budget 78 M€, 18.5 M€ EC-contribution), Reykjavik (ECTOS, 2001-2005) as well as Perth (STEP, 2004-2007). [CUTE, 2005, p. 9]. FP6 included the production, storage and distribution of alternative fuels and the exploration of synergies between sector and technology pathways such as linking biofuels and H_2-technology pathways. Medium-and-longer-term research activities focused on all sizes of FCs and their applications. The overall target was to enable FCs to compete with conventional combustion technologies and to make many applications cost efficient by 2020. [EC, Work programme, 2004, p. 7-28] In 2006, the Berlin HyFleet project (finally operating four H_2ICE standard MAN A21 NF Lion engine buses) was integrated; the overall **HYFLEET:CUTE** project received 19 M€ EC-funding. [EC, DG Research, 2006, p. 23]

The **FP7** (2007-2013, budget of 50.5 G€), Thematic Area "Energy" (2.3 G€) focused on increasing energy security and the need to dramatically curb GHG-emissions.

Finally, there is an increasing trend in EU funding towards H_2FC-research over successive FPs (see Figure 4 1, without additional funds for JRC direct actions on H_2FC). Funds are matched by an equivalent amount of stakeholder investment.

The **Contact Group Alternative Fuels,** established by the EC in 2002, asked experts from industry, academia and non-governmental organisations on the technical and economic basis for the further development of alternative road fuels (natural gas, hydrogen, Biomass to Liquid, LPG). Hydrogen fuel was seen as a potential future energy carrier due to its broad feedstock flexibility, including renewables, achieving a share of a few percentage points in road transport by 2020. Drivers for the H_2-market entry could be the linkage of hydrogen and natural gas fuel infrastructures and technologies, the use of H_2ICE, support to R&D in high-volume/low-CO_2-hydrogen-production pathways as well as to large-scale lighthouse projects comprising all key elements of an H_2-economy. FCVs were projected to offer high energy efficiency potential and to become competitive, following cost reduction and reliability enhancement of FCs. [AFCG, 2003, p. 2-3]

CHIC, the "Clean Hydrogen in European Cities Project" (2010-2016, budget of 81.8 M€, 26 M€ contribution of the EU's FCH JU) is entitled to move H_2FC-buses to full market commercialisation by 2015. The project adds 26 H_2FC buses to daily public transport operations. The technical project goals also relevant for marketing of FC-cars are increasing FC-lifetime to more than 6,000 h, making availability of all FC-buses greater than 85% and reducing fuel consumption to less than 13 kgH_2/100 km. Requests to fuelling stations are: capacity of 200 kgH_2/day, average station availability of 98% (based on operation time), H_2-production efficiency between 50 and 70%, H_2-OPEX[81] costs less than 10 EUR/kg. [Pester, 2012; CHIC, 2012]

The key challenge of the **HORIZON 2020** programme (2014-2020, budget of 80 G€), the successor of the FPs, is the transition to a reliable, sustainable and competitive energy system, in the face of increasingly scarce resources and energy needs and climate change. Activities include 'Alternative fuels and mobile energy sources' as well as an **integration of hydrogen to the energy system to provide flexibility through enhanced energy storage technologies**. The 2014/15 work programme is focusing on short-term measures to support the EU 20/20/20 targets.

Figure 4-2: Overview of international and European hydrogen projects and programmes

The EU established **Joint Technology Initiatives (JTI)** under the FP7. The **Fuel Cells and Hydrogen (FCH) JTI** (budget of 470 M€, max. 50% funding) implemented the respective

80 http://ec.europa.eu/research/fp5/key.html, 28.12.2007

81 OPEX: Operating expenses related to the production and distribution of H_2, e.g. wages for employees, R&D, raw materials; without taxes, debt service or other expenses inherent to the business operation but unrelated to production. [http://financial-dictionary.thefreedictionary.com/OPEX; 06.10.2012]

RTD-programme with the involvement of stakeholders from industry, research centres, universities and regions. The JTI is operational through the legal entity '**Fuel Cells and Hydrogen Joint Undertaking (FCH JU)**'.The FCH JU advises on the research agenda, evaluates scientific achievements through its Scientific Committee, publishes Implementation Plans, see *Figure 4-3*, and organises the respective calls for proposals. The European Parliament, on recommendation of the Council, finally agrees on the budget of the FCH JU. [EC, European Council, Regulation 521/2008] The FCH JTI's roadmap for a European FCV-rollout anticipated between M0.4-1.8 FCVs by 2020; thus, providing only a small contribution of H_2FCVs to the EC's 20/20/20 targets. However, H_2FCVs are expected to play an important role in achieving the EU's vision of reducing GHG-emissions by 60-80% by 2050. FCH JU assumed that the climate policy and decreasing oil reserves will drive the process of FCV-commercialisation after 2020. **Finally, by 2050 hydrogen shall be competitive with other zero-emission transport energy carriers**. An H_2-infrastructure shall be available based on large centralised liquefaction, on-site production facilities and a network of pipelines, partly based on the natural gas network, with the capability to serve mass market demands.[82] The FCH JTI was integrated together with the 'Smart Cities Initiative' and the 'European CO_2-Capture, Transport and Storage Initiative' to the **European Strategic Energy Technology Plan** (SET). SET shall promote cost-effective low carbon technologies. [EC, Set-Plan, 2010]

Application Area	**Targets 2010**	**Targets 2015**	
		Volume	**Cost and Technology**
Transport & Refuelling Infrastructure Budget M€ 150	~ 10 more single road sites plus mobile deployment to existing sites to fill up to 50 vehicles ~ 20 buses on 3 sites with refuelling capacity	~ 500 LDVs (mainly cars) at 3 additional sites with 3 new stations ~ 500 buses at 10 EU filling sites (>7 new ones), capa. >400 kg/d	• System ~ 100 €/kW • Durability in car propulsion systems 5,000 h • Roadmap on establishing a commercial EU H_2-refuelling infrastructure
Hydrogen Production & Distribution	Appropriate H_2 supply chain (incl. fuel purity) to match Transport, Stationary and Early Markets requirements. For 2015 10-20% of H_2-demand should be produced via carbon free/carbon lean processes		• H_2-cost deliv. at fill. stat. < 5 €/kg (0.15€/kWh) • Improved H_2-storage system density (9%wt H_2)
Stationary Power Generation & CHP	3-7 MW_{el} installed in the EU for pre-commercial demonstration	~ 100 MW installed electric capacity	• 4-5 k€/kW for micro CHP, 1.5-2.5 k€/kW for indust./comm. units
Early Markets	500 new units in the EU: • 50 UPS/back-up power • 20 industrial and off highway vehicles • ~ 400 portab./micro FCs	k14 new units in EU: • k1 UPS/back-up power • 500 industrial and off-highway vehicles • k12-k13 port./microFC	

Figure 4-3: Targets of the JTI Multi-Annual Implementation Plan 2008-2013[83]

It is worth noting: it is only 15 years since H_2FC-technology entered the European research area. The main achievements are that 70-MPa-H_2FCV-technology has been selected as the hydrogen car technology to follow; bus, car and infrastructure demonstration projects have been implemented; the standardisation framework is well developed; safety issues are understood and interdisciplinary cooperation networks have emerged to promote FCV-technology market entry.

82 http://www.fch.europa.eu/, 15.11.2015; FCH JU, 2009, p. 19

83 http://www.fch.europa.eu/, 15.11.2015; FCH JU, 2009, p. 7-12

4.1.1 Specific European hydrogen programmes

Several thematic H_2FC-projects were financed by the EC to prepare for the market introduction of the technology. The main projects and results are summarised in the following:

In 2002, the EC established a **High Level Group (HLG) on Hydrogen and Fuel Cells** involving nineteen European H_2-stakeholders from industry and research institutions to facilitate a high level strategic discussion and to develop a European consensus on the introduction of H_2-energy. In 2003, the HLG presented a vision report, including a draft of a European Roadmap (see *Figure 4-4*) which formed a basis for the following calls for FP6 and FP7. The long-term funding needs for the transition to an H_2FC-economy were estimated at some hundreds of billions of Euros.

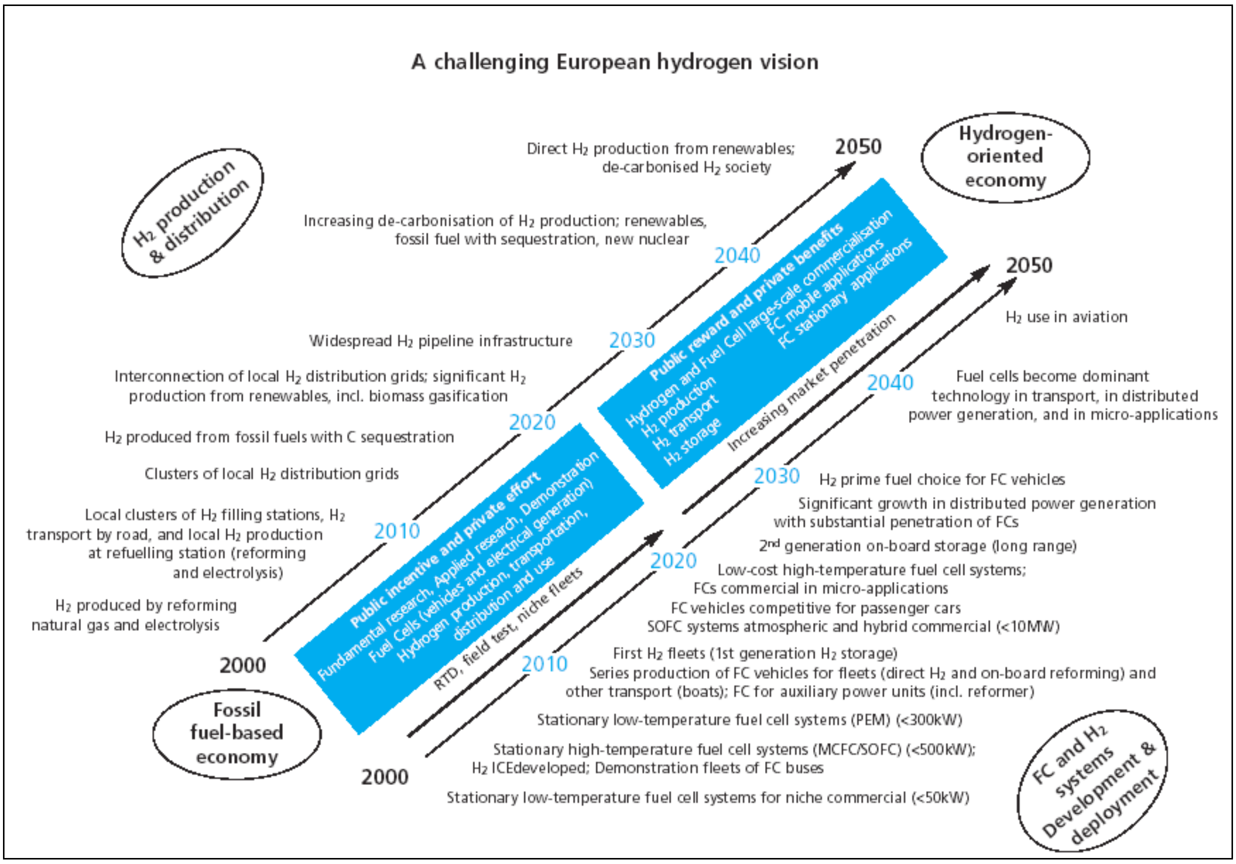

Figure 4-4: HLG's European Roadmap [HyNet, 2004, p. 23]

HyNet (European Thematic Network on Hydrogen Energy, 2001-2004, budget of 7.9 M€, FP5 funding of 4 M€) brought together twelve contractors (NorskHydro, Shell Hydrogen, BP, Air Products, ICI, Dera, BMW, TotalFinaElf, EniAgip, Hydrogen Systems, EtaIng and CEFIC) and more than 70 supporting partners from academia and industry. The network aimed at initiating consensus on a vision and strategy to build a European H_2-infrastructure and to bundle H_2-RTD. HyNet named **the success factors for the H_2-economy** as follows: use of innovative H_2-technology, contribution to energy security, climate protection and industrial competitiveness. [HyNet 2004, p. 25] HyNet developed a scenario for the infrastructure build-up (see *Figure 4-5*). Around k10 H_2-filling stations would distribute the fuel once the H_2-economy was fully implemented in Europe. This would equal 900 vehicles per filling station and a supply of 150 MgH_2/a per station. This car density per filling stations is comparable to the German one in the 1980s (taking only street filling stations into account). The HyNet-timeframes and favourised technologies (e.g. LH_2-, ICE- and onboard reforming technology) are outdated or obsolete from today's point of view. The industry is concentrating on

Compressed Gaseous (CG) H_2FC-technology. However, HyNet's idea of pre-competitive public-private-partnerships to introduce (annually x-100) new vehicles in Lighthouse Projects was partly realised in the CEP, the H_2-initiative and the FCH JU.

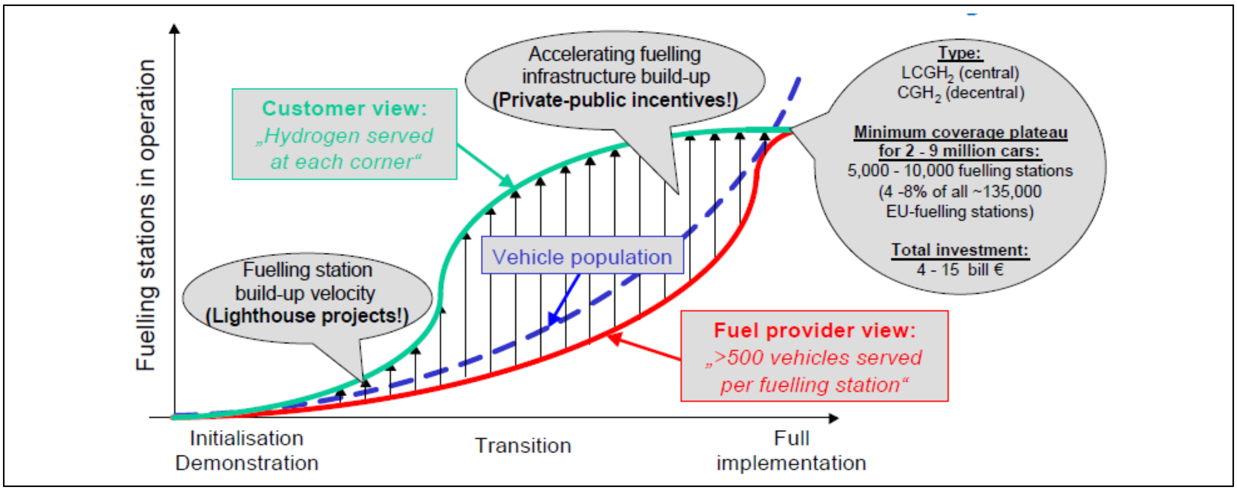

Figure 4-5: HyNet's scenario of an H_2-filling station build-up [HyNet 2004, p. 10]

HyNet finally led to the FP6 project "**HyWays - The Development and Detailed Evaluation of a Harmonised European Hydrogen Energy Roadmap**" (2004-2007, seven Member States). HyWays' results formed the basis for the design of the specific EU funding programmes, mainly FP7. HyWays emphasised that several H_2-production pathways exist at price levels comparable to conventional fuels ensuring a relatively stable H_2-production price. Natural gas, biomass and wind energy-based pathways were selected H_2-production options by all Member States. HyWays predicted that hydrogen could substitute 40% of total road transport oil consumption (100 Mtoe) until 2050. 45% of the H_2-demand could be covered by electrolysis using renewable and nuclear energy in 2050.

HyWays described a European **H_2-infrastructure rollout plan**. HyWays evaluated the poor utilisation of filling station capacities as being critical during the H_2-introduction phase. The total cumulative investment for building-up an infrastructure for about M16 H_2-vehicles was estimated at 6 G€ by 2030. HyWays calculated the break-even point, compared with the savings gained from replacing conventional fuels and vehicles, at M25 H_2-vehicles (3 €/kgH_2, FC: 50 €/kW, tank 5 €/kWh, by 2025-2035). HyWays predicted that approximately 50% of the road transport sector (mainly LDVs and city buses) could make a fuel shift towards hydrogen. HDVs and long distance coaches are expected to switch to alternative fuels (e.g. biofuels). HyWays confirmed the role of **hydrogen as an energy storage** option and its potential to facilitate the large-scale introduction of FC-technology and intermittent resources. [HyWays, 2008, p. 2] HyWays predicted that the total net impacts on employment shall amount to +M0.2-0.4 labour years by 2030. The production of dedicated propulsion systems shall contribute to maintain high skilled labour in Europe.

For comparison, a study ordered by **Linde** calculates with M40 H_2-vehicles in Europe by 2030. This fleet would need the production, transport and distribution of about 7,000 GgH_2 to supply about k16 urban H_2-filling stations and additional highway stations connecting the H_2-regions. Highly urbanised countries have the largest filling station demand by 2030, e.g. **Germany about k5**, the UK k3.4 and France k2.7. The scenario assumes a delayed H_2-production start due to the use of byproduct-H_2 during the early phase. By 2030, the cumulative H_2-fuel costs depend highly on production and distribution technology chosen as well as the market penetration rate (8-33 G€). Centralised production is cheaper, the use of centralised steam reforming and distribution by trailers is the most economical solution because these plants are able to better use their capacity and get the most out of the investment made. [Hart, 2005] In the mid-term, Linde sees an investment need of 3.5 G€ for the construction of a European H_2-infrastructure of k2.8 filling stations to supply M6.1 cars by 2020, the supply of M1.9 German H_2-cars would need an investment of 870 M€. These costs seem to be low compared with investments in other European infrastructure projects. Infrastructure development would start in highly urbanised areas; these areas would be linked by corridors. This would allow one third of the European population to be connected to H_2-infrastructure. The erection of H_2-filling stations away from population centres would be postponed. A cash-flow analysis showed that investments for the production and distribution of hydrogen would recoup – with regional differences – within 10 to 15 years, a time period that is not unusual for projects of this magnitude. [Linde, 2005] This scenario appears realistic for the coming years. Progress on the development of a European H_2-filling station network may be followed at www.h2stations.org.

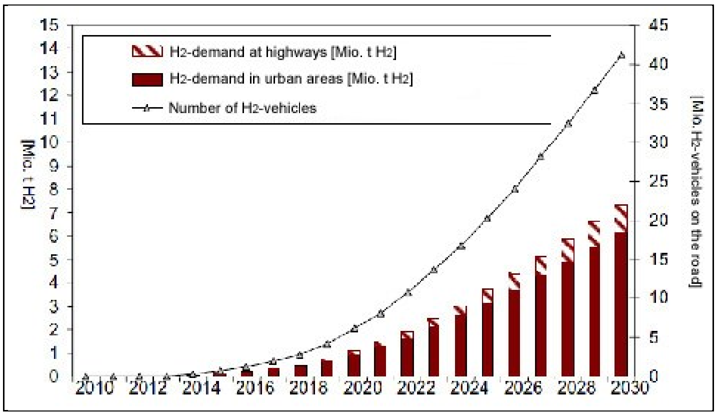

Figure 4-6: Number of H_2-vehicles and H_2-demand by 2030 [Hart, 2005, p. 3][84]

Hydrogen will play an important role as a fuel in future transport in Germany. This is the thesis of the **GermanHy** project after investigating three scenarios[85] varying the availability of fossil fuels and political targets on climate protection. The study was elaborated in co-operation with NOW[86] and was also used to design the NIP. General assumptions include the cost reduction in FC-LDVs reaching the level of modern diesel vehicles, a minimum RES-share of 20% in primary energy consumption by 2020 (for details see study itself). GermanHy assumed very low energy efficiency progress for conventional fuels. For example, regulation 443/2009 specifies a target of 95 gCO_2/km for 2021. In GermanHy car fleets reach these values by 2040 and only in the ambitious scenarios. GermanHy examined in detail the **energy sources that could cover cost-efficiently the growing H_2-demand** by 2020, 2030, 2050. H_2 from biomass will reach competiveness early but this resource is limited. Off-shore wind energy and electrolysis will follow by 2050. GermanHy included fossil fuels and CCS into its production portfolio. However, these pathways lack public acceptance for public co-funding. [GermanHy, 2008, p. 8, 24-25, 43] The mid-to-long-term H_2-fuel costs were estimated to 12-15 ct/kWh (w/o tax), i.e. 4-5 €/kgH_2 (see *Figure 4-7*). This equals to the 2015 target of JTI MAP, see Figure 4-3. The use of 50% renewable energies will cause extra costs of 3 ct/km by 2030 (1.5 ct/km by 2050). [GermanHy, 2008, p. 43] The H_2-fuel consumption is given with 0.9 kgH_2/100 km in a 2010 FCV, this corresponds to the current Mercedes FCB-class consuming about 1.0 kgH_2/100 km. [GermanHy, 2008, p. 36-37, 43, 46, 52]

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84 The study includes the development of an infrastructure in the 50 largest European urban areas (> M1 inhabitants) to reach the highest delivery potential. The infrastructure shall be erected in four phases during five years. New urban areas are added in groups and are connected with streets.

85 **Shortage of Resources Scenario (SRS)**: Massive shortage of fossil resources, crude oil price 2020/2050: 248/202 USD/bbl, GHG-reduction targets 2020/2050 -20%/ -40%.
Moderate Development Scenario (MDS): Conservative trend progression, crude oil price 2020/2050: 54/111 USD/bbl, GHG-reduction targets 2020/2050: -20%/ -40%.
Climate Protection Scenario (CPS): Ambitious climate protection policies, crude oil price 2020/2050: 54/111 USD/bbl, GHG-reduction targets 2020/2050:-40%/ -80%.

86 Elaborated by dena, Forschungszentrum Karlsruhe, Fraunhofer ISI, LBST, Wuppertal Institut.

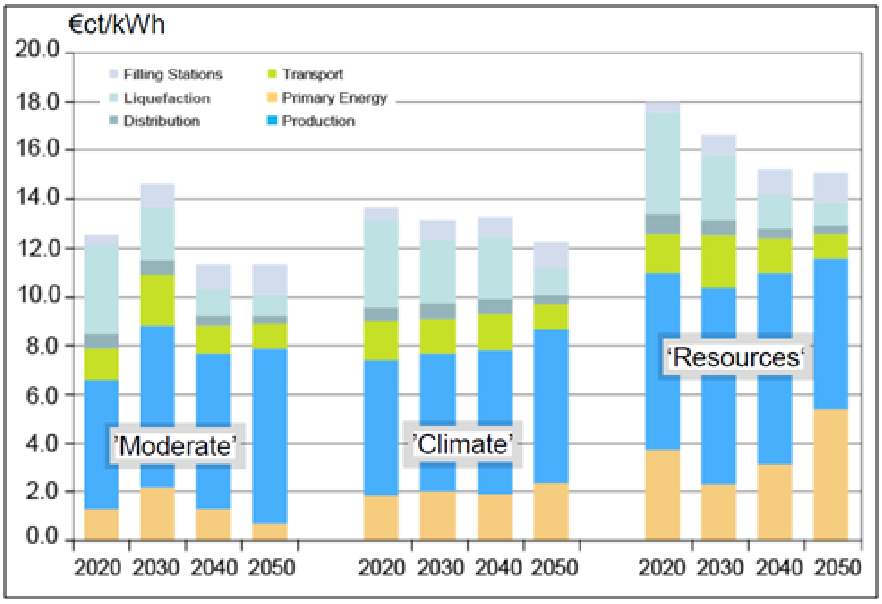

Figure 4-7: GermanHy's H_2-costs [GermanHy, 2008, p. 10]

Until 2030, the trailer transport of centrally produced LH_2 to end-users shall dominate to integrate offshore wind and by-product hydrogen. Additional H_2 is produced onsite (re-formation, electrolysis) in the short-term. With growing demand, GH_2 is distributed in pressurised pipelines (20% by 2030, 80% by 2050). GermanHy assumed a fast H_2-market entry. The **H_2-infrastructure** shall be introduced gradually, starting with large conurbations (Berlin/Hamburg/Ruhr area), followed by more densely populated areas, preferably with a high average income (Rhine-Neckar/Rhine-Main/Munich area). These initial centres could be inter-connected by a network of 180 highway stations with a distance in between of 30 km, covering two thirds of the German highway network by 2020. However, a H_2-station network is also needed in medium and small towns. There will be a difference in capacity use and cost effectiveness of rural and urban H_2-stations in Germany. The GermanHy distribution &infrastructure costs are 21 G€ for M7.1 LDVs by 2030, but after H_2-vehicles reached a share of 15%, the erection of a more extended infrastructure will not substantially increase H_2-costs. As long as the access to an H_2-infrastructure is limited in more rural areas until 2030, the market share of H_2-vehicles is expected to be limited to less than 20%. [GermanHy, 2008, p. 37] **The fleet average of H_2-vehicles may be as low as 20 gCO_2/km TtW- and 36 gCO_2/km WtW-emissions**, if hydrogen is generated from renewable energies or fossil energies using CCS. [GermanHy, 2008, p. 10] The GermanHy roadmap is depicted in *Figure 4-8*. However, the level of realisation of the predicted achievements of GermanHy shows that the difficulties of technology market introduction are often underestimated.

Furthermore, the industry, in close cooperation with several research organisations, also carried out several concrete thematic projects which required a high degree of cooperation. Examples include:

"Hydrogen Storage Systems for Automotive Application (StorHy)" (2004-2008) was an FP6 Project under the lead of MAGNA STEYR Fahrzeugtechnik, including 34 European partners, in particular, from the European automotive industry (BMW, DaimlerChrysler, Ford, MSF, PSA, and Volvo), gas suppliers (Air Liquide, Linde), testing and certification bodies as well as research and academic institutions. StorHy developed robust, safe and efficient on-board vehicle H_2-storage systems, i.e. pressure vessels, cryogenic and solid storage and worked on recycling of vessels. StorHy **developed 70 MPa lightweight CGH_2-vessels**, including production processes, according to the set of specifications (StorHy Targets 2010) given by the car manufacturers, for details see the very extensive StorHy-documentation.

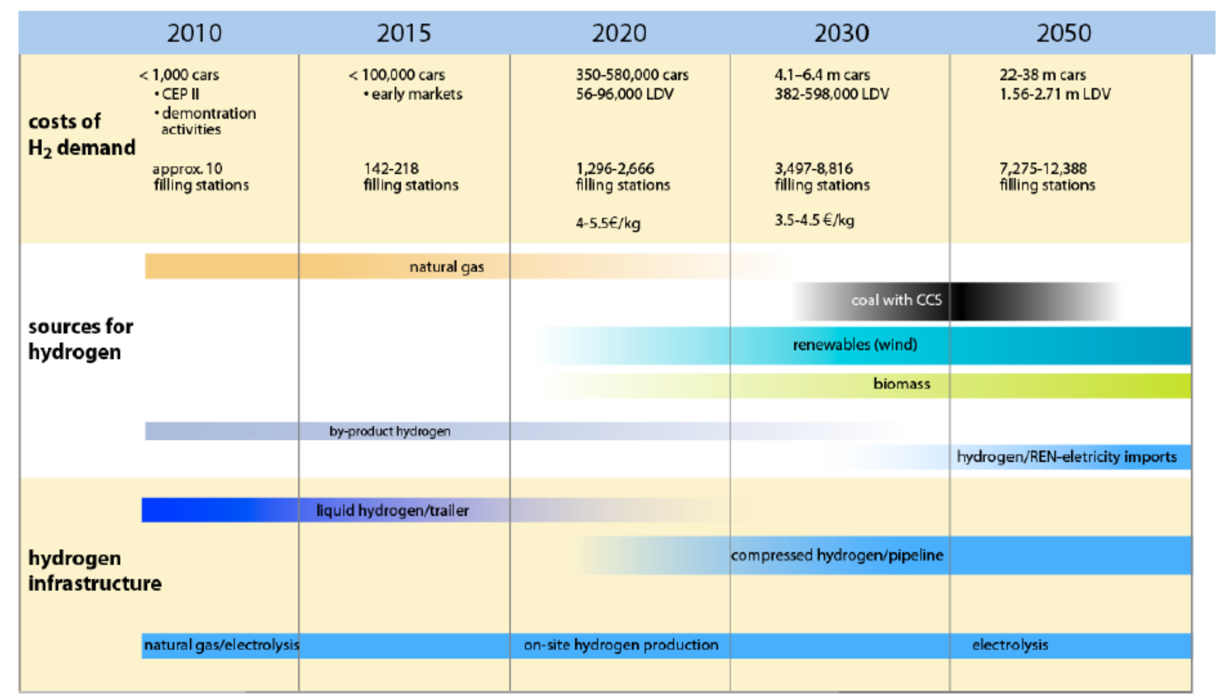

Figure 4-8: The GemanHy Roadmap [GermanHy, 2008, p. 17]

StorHy developed **70 MPa H_2-fast filling technologies and processes** (1.2 kgH_2/min as objective). The target was to completely fill a 70 MPa 150 l tank in less than four minutes, while avoiding overheating the composite vessel structure due to quasi-adiabatic expansion. The project successfully assessed Type III tank (metallic liner) fuelling at ambient temperatures (90% was possible within 3-4 minutes, a 100% filling needs H_2-pre-cooling to 0°C). Type IV tanks use a cold fuelling process to reach the time target in order to prevent local overheating caused by the weak heat conductivity of the composite material. StorHy showed that energy consumption for cooling down to -40/-80°C is equivalent to energy consumption due to compression. StorHy carried out safety studies and pre-normative research, e.g. procedures were elaborated for testing cylinders during their whole lifecycle. The permeation behaviour of vessels and systems was investigated. [StorHy, 2008, p. 32-37]

HySafe (2004-2009, funding M€ 7) was a Network of Excellence bringing together 25 research and industrial partners (automotive, gas and oil, chemical and nuclear). HySafe was one of the first IPHE projects (see section 4.1.1). It was aimed at facilitating the safe introduction of H_2-technologies and applications. HySafe elaborated several studies, an overview of experimental facilities in Europe as well as scenarios of H_2-releases and of safety issues concerning H_2-vehicle accidents in tunnels. It implemented an Incident and Accidents Database, see https://h2tools.org/lessons. Finally, it resulted in the foundation of the "European Hydrogen Safety Centre". [http://www.hysafe.org/, 29.07.2012]

The project "**Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst**" (NaturalHy, 2004-2009, M€ 17.3 total budget, M€ 11 EC funding) was an FP6 Project under the lead of Nederlandse Gasunie, including 39 European partners. The project assessed the capability of the medium pressurised natural gas network (4-8 bar) to distribute various mixtures of H_2 and CH_4 given appropriate modifications.

The physical and chemical properties of hydrogen and methane differ significantly, thus the addition of a certain percentage of hydrogen to natural gas might have a direct impact on combustion properties, diffusion into materials and the behaviour of the gas mixture in air. NaturalHy defined the conditions under which hydrogen could be added to the natural gas network with regard to acceptable safety risks, benefits, impact on system integrity as well as consequences for the gas quality management and for the end-user. It developed technical options to separate hydrogen from the methane-hydrogen (CH_4-H_2) mixture and assessed respective socio-economic and lifecycle aspects, see project report. [NaturalHy, 2010, p. 3] The NaturalHy-project identified the **key risks**[87] **of failure** on the high pressure pipeline system or on the low pressure pipelines internal to people's property and from low level leakage due to minor imperfections. The risk assessment for the CH_4-H_2-mixture considered:

- Probability of an accidental release from different parts of the gas infrastructure and the probability of ignition of the gas mixture,
- Assessment of the consequences of gas dispersion, fire and explosion involving CH_4-H_2-mixtures by modelling and conduction of large scale and laboratory scale experiments,
- Data on the characteristics of the CH_4-H_2-mixtures, in particular, in relation to turbulent combustion and ignition energy.

Main results are: The **leakage rate of incidental leakages**, e.g. as a result of poor, damaged joints or minor defects in the pipe wall, is typically from lower pressure parts of the system and less than 1% of the gas conveyed. It normally presents no safety hazard. The H_2-addition to the system reduces the mass leakage slightly, e.g. for a mixture$_{20\%}$[88] the total mass leakage is reduced by a factor of 0.91 and the CH_4-leakage by 0.89, giving a benefit on the GHG-emissions. However, if the system continues to operate at the same pressure, a CH_4-H_2-mixture has a reduced energy delivery rate.

The **gas build up characteristic** of CH_4-H_2-mixtures is similar to that of natural gas and no H_2-separation occurs. The **overall conclusion on safety** is that adding 20-30% H_2 will not make a major difference to consequences (fires and explosions) of accidental releases. Even mixture$_{40\text{-}50\%}$ could be achieved without unacceptably increasing the risks, nonetheless, mitigation measures to reduce explosion severity in certain situations should be applied.

Up to mixture$_{50\%}$ **failure frequency in the transmission pipeline system** arising from fatigue crack growth of sharp crack-like defects, where dissociation of H_2-molecules into atomic hydrogen detrimentally affect the material properties of the steel, does not increase. The assessment of the **durability of steels for transmission pipes** included the fracture toughness of steel, in particular X52 and X70[89]. NaturalHy found that up to mixture$_{50\%}$ effects on the fatigue behaviour may be acceptable depending on steel type and operational conditions. [NaturalHy, 2010, p. 21-6] The **durability of polymers for distribution pipes** showed that Polyethylene (PE) is sensitive to gas permeation. Hydrogen diffuses quicker than methane and with larger quantities, e.g. 6-7 times in a test at 1 MPa, 16°C, diameters of 110 and 160 mm. However, the performance of PE and PVC is not alarming from an engineering point of view. Hydrogen has no significant effect on the aging of PE. The calculated theoretical permeation for a PE distributing pipe at 0.4 MPa, mixture$_{20\%}$ is 2.3 l H_2/km/d compared to 1.1 l CH_4/km/d.

The **reliability of domestic gas meters with polymer membranes** is within currently accepted standards up to mixture$_{50\%}$. Also, the currently used gas-valve combinations of

87 Risk was defined as the combination of the likelihood of an event and its consequences. The personal risk is the likelihood of a person at a particular distance from the event becoming a fatality; the societal risk is directed at the population as a whole.

88 Index indicates that 20% H_2 is blended to the natural gas.

89 API 5L of the American Petroleum Institute provides standards (manufacturing process, dimensions, couplings, quality, testing) for pipes suitable in use for conveying gas, water and oil in the natural gas and oil industries, e.g. standard Grade X70 is suitable long-distance pipelines, X50 for distribution networks, for details see https://law.resource.org/pub/us/cfr/ibr/002/api.5l.2004.pdf

inner grids were proven to be suitable up to mixture$_{50\%}$. [NaturalHy, 2010, p. 27-31] NaturalHy also tested the performance of current **end-use applications**. Modern pre-mixed boilers operated up to mixture$_{50\%}$ with no problems under all seasonal conditions, older pre-mixed boilers were tolerant against up to mixture$_{40\%}$. Fuel-rich domestic boilers are prone to light-back, limiting the amount of hydrogen that can be added safely. The exact level for the acceptable mixtures depends strongly on the natural gas quality. However, a limit is marked at mixture$_{18\%}$ to a H-gas showing a minimum Wobbe index. For poorly adjusted domestic appliances and/or unfavourable natural gas conditions, no H_2-addition is allowed. Stationary gas engines and gas turbines need individual readjustment and/or modifications. NaturalHy also investigated several membranes for separating hydrogen from the CH_4-H_2-mixture with extraction rates of 98% using carbon membranes at low costs. [NaturalHy, 2010, p. 35-40]

HySafe, StorHy and NaturalHy answered important technical and safety questions. They indicated future technical potentials and limits of H_2FCV-technology. HyNet, HyWays and GermanHy were more political projects showing in quite optimistic timeframes the opportunities of the technology to contribute towards the energy and climate targets of the EU.

4.1.2 Various corridor projects

There are various corridor projects in Europe and the US to overcome the infrastructure problem. In addition, there are also co-operations between the corridor programmes, e.g. the CEP and the Scandinavian Hydrogen Highway Partnership.

Scandinavian Hydrogen Highway Partnership

The **Scandinavian Hydrogen Highway Partnership** includes three national H_2-organisations: HyNor (Norway), Hydrogen Link (Denmark) and Hydrogen Sweden. It is aimed at making Scandinavia one of the first regions in Europe where hydrogen is available and used in a network of refuelling stations. Denmark's first H_2-refuelling station opened in Copenhagen in 2009, a second 70 MPa H_2-filling station opened in Holstebro in 2011.[90] In 2012, the Danish Energy Plan 2020 established many initiatives to introduce an H_2-infrastructure and FCVs with the overall aim of achieving 100% fossil independence by 2050. The Program includes FCV tax exemptions until 2015. In Denmark 180% tax and 25% VAT is applied on the base vehicle price meaning that a k€ 17 petrol vehicle reaches an end-price for the vehicle-user of k€ 50. Hyundai shipped the first 200 ix35 FCVs to Denmark in 2014. Fifteen of the vehicles are already used by the city of Copenhagen as part of their municipal fleet supporting Copenhagen as 'Green Capital in 2014'.[91] HyNor is targeted to build an initial H_2-corridor of 600 km length consisting of seven stations between Stavanger and Oslo. The project is quite challenging because of wide variations in climate, topology and very cold seasonal temperatures. In 2012, Statoil pulled back from hydrogen to focus on its core business. [FuelCell Today, 2012, p. 3] However, 6 stations have been operational in 2015, the Starvanger station is under construction. [http://www.scandinavianhydrogen.org/h2-stations, 15.11.2015]

Green Corridor Project foresees the construction of an H_2-filling station every 100 km along the section Munich-Verona of the Brenner motorway (A22) along the European Corridor 1 distributing 'green' hydrogen produced through electrolysis by using different types of renewable energy sources. The first filling station opened in Bozen in 2015. The Bozen project is part of the CHIC project and also includes five FC-buses.

[90] http://www.scandinavianhydrogen.org/, http://www.hydrogenlink.net/eng/network.asp, 25.02.2014

[91] http://www.scandinavianhydrogen.org/shhp%5D/news/danish-government-to-launch-hydrogen-infrastructure-program-continue-fcev-tax-exemptions-; http://www.hit-tent.eu/2014/01/hyundai-ix35-brint-launched/, 15.02.2014

The **British Columbia Hydrogen Highway**, Canada project was launched in 2004 (for the 2010 Olympic and Paralympics Winter Games). Two fuelling stations produced hydrogen through electrolysis using electricity generated from hydropower to operate 20 FC-buses; the largest bus fleet worldwide. The project was supported by the H_2i campaign. However, when the Whistler H_2FC-bus demonstration project expired in 2014, the buses were replaced with diesel buses. [HydrogenHighway, no year]

The **California Hydrogen Highway and California Fuel Cell Initiative** was initiated in 2004 by Executive Order S-07-04 targeted [...] "so that by 2010, every Californian will have access to hydrogen fuel, with a significant and increasing percentage produced from clean, renewable sources; [...]"[92] The mid-term Californian target is to implement an infrastructure to support one million ZEVs by 2020 and to have M1.5 ZEVs on the road in an expanding market by 2025. (supporting the targets of the **Californian Global Warming Act**). Currently 48 mostly government-funded Californian H_2-stations are under development (8 are open, 2 for buses). All public stations supply hydrogen at a pressure of 35 MPa and 70 MPa. The progress on installation of filling stations is published at http://cafcp.org/index.php?q=stationmap. No information on FCV-numbers are currently available.

The **California Fuel Cell Partnership (CaFCP)**, founded in 1999, is a collaboration of auto manufacturers, energy providers, government agencies and FC-technology companies to promote the commercialisation of H_2FCVs. The CaFCP served as an example for the foundation of the CEP in 2002. The partnership aims to ensure that vehicles, stations, regulations and people are in step with one another as the technology comes to market. [http://cafcp.org/aboutus, 13.10.2012] The CaFCP elaborated "A California Road Map: The Commercialization of Hydrogen Fuel Cell vehicles" to guide the placement of H_2-filling stations during the pre-commercial phase (2012–2014), giving early-adopters the confidence that they can fill up near their homes at high-performing, state-of-the-art stations with a high availability, i.e. 24/7 operating hours, safe operation, conventional payment methods, no requirements for personal identification or classroom training requirements. CaFCP estimated H_2-station costs as depicted in *Figure 4-9*. In order to launch the early commercial market, a need was identified for 68 strategically placed stations to be operational by the end of 2015. [CaFCP 2012 (1), p. 13-24; CaFCP 2012 (2), p. 3-18; Stephens-Romero et.al., 2011]

Station timing and size	Capital costs	Annual operating expenses	
Stations built in 2014		Cost without H_2-supply	Costs at max. load
100-170 kg/day	$0.9M	$75k	$100k
250 kg/day	$1.4M	$80k	$117k
Stations built 2015-2017			
250 kg/day	$0.9M	$75k	$112k
400-500 kg/day	$1.5M-$2.0M	$81k	$167k

Figure 4-9: H_2-station baseline cost assumptions [CaFCP, 2012 (1), p. 24]

During the commercialisation phase (2015-2017) balancing customers' need for station coverage with station capacity utilisation is important. Within the clusters, all 68 stations shall be available within a maximum travel time of six minutes. This should enable the launch of k10-30 FCVs, which is planned for the end of 2016. By the end of 2017, an estimated number of k53 FCVs and 100 filling stations shall be in use. For comparison, the Californian population amounts to M37.7 and M22 cars have been registered.[93]

[92] http://www.hydrogenhighway.ca.gov/media/execorder_s704.pdf; 24.06.2012
[93] http://quickfacts.census.gov; http://dmv.ca.gov/portal/dmv, 20.10.2012

By the end of March 2016 the Japanese government plans to set up about 100 commercial H_2-stations, mainly in major cities such as **Tokyo, Osaka and Nagoya**, to encourage the use of FCVs. The first station was opened in 2014 and is operated by Iwatani Corp (major provider of industrial gases in Japan). About 40 stations are currently planned in 11 of the 47 prefectures. Japan is an interesting market due to the relatively small landmass (0.378 Mkm², with 61% concentrating on the main island of Honsu). Toyota Motor Corp. launched the first retail FCV-model by the end of 2014 with a sticker price of around 7 M¥, i.e. 51 k€.[94]

4.1.3 Main German programmes

The co-operation "Verkehrswirtschaftliche Energiestrategie" (VES, Transport Energy Strategy) between German politics and private companies was founded in 1998. It was targeted at developing strategies to ensure a global leading role of the German car industry in alternative fuel technologies. Contribution to CO_2-reduction, to energy efficiency increase, to reduction in oil dependency and to the extension to a European initiative have been defined as **guiding principles for the work of the VES**. The VES partners agreed on a joint fuel strategy. Originally ten alternative fuels and their production pathways were selected and analysed according to environmental and economic criteria (see *Figure 4-10*).

Natural gas, methanol and hydrogen were selected as the three most promising alternatives, but, initially, there was no clear favourite. The VES, argued that the mineral oil industry and customers defeated the introduction of methanol due to its toxic and corrosive characteristics. [VES, 2007, p. 47, 49] The WtW-analysis clearly showed that only the RES-use would allow for the requested GHG-emission reduction in 90% and more (see *Figure 4-11*). Only three options showed less than 50 gCO_2/km, i.e. CGH_2-FCVs, LH_2ICE and BtL ICE, all operated on biomass.

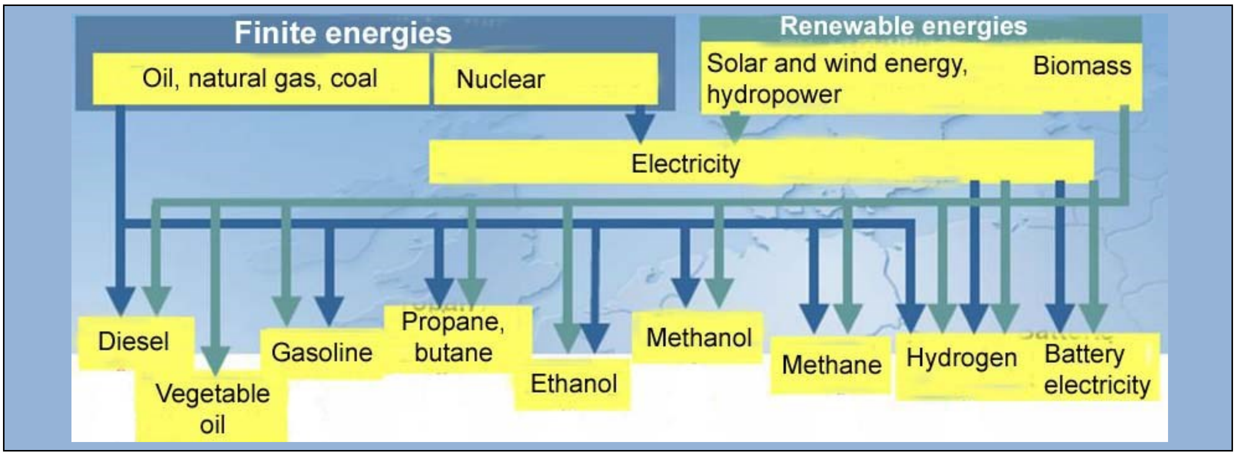

Figure 4-10: Possible car fuels analysed by the VES [Scheuerer, p. 6]

The VES Steering Committee advised to agree on only one fuel, considering the above mentioned guiding principles of the partners' Memorandum of Understanding. The result clearly led to hydrogen as the most promising long-term sustainable transport fuel. The 2001 status report highlighted the main strategic advantage of hydrogen to produce it from various regenerative sources in large amounts avoiding GHG-emission and reducing supply risks. In addition, the use of hydrogen includes a high innovation potential which would allow the German industry to enter new fields of economic growth. Green hydrogen has the potential to finally decouple energy consumption from GHG-emissions. [VES, 2001, p. 1-6]

[94] http://www.bloomberg.com/news/articles/2014-11-18/toyota-s-63-000-mirai-gets-japan-support-mirroring-prius, 21.12.2014

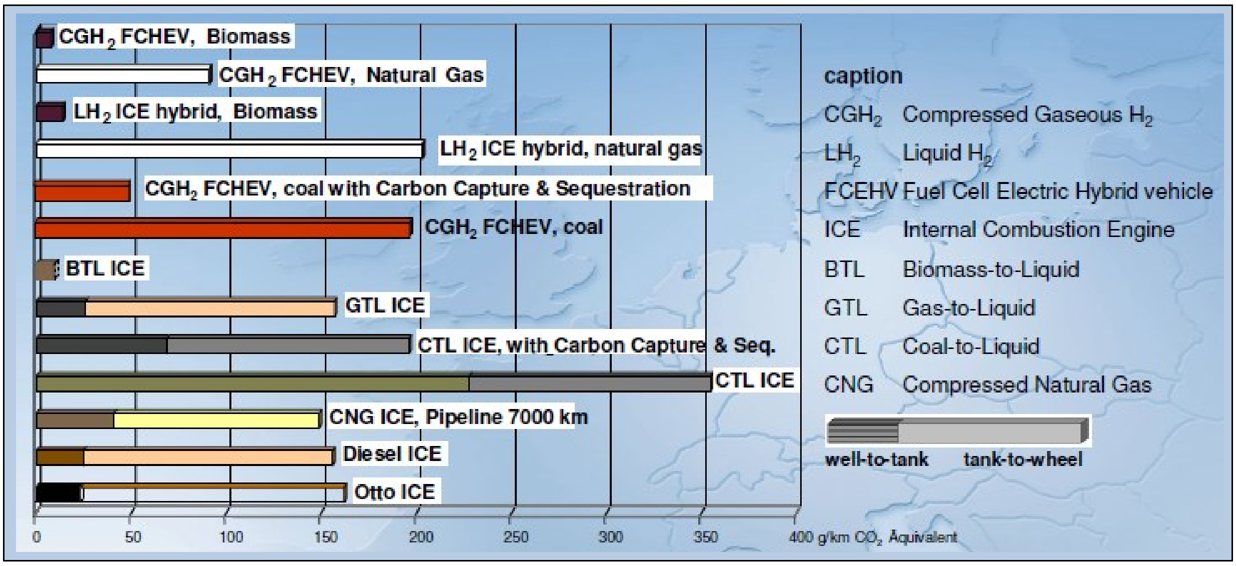

Figure 4-11: WtW-GHG-emission comparison of possible car fuels [Scheuerer, p. 7]

In 2002, the German government elaborated its sustainability strategy „**Perspektiven für Deutschland**“ (Perspectives for Germany). The decoupling of economic growth from energy consumption is the long-term target of the German and **European (2006) sustainability strategy**. The efficient use of energy, the use of renewable energies and sustainable mobility were declared core areas of the German sustainability strategy. It demanded a faster implementation of innovative technologies to reduce transport emissions, the VES was included as a concrete measure. The **efficient use of hydrogen in FCs was picked up under the thematic complex of renewable energies**. The development of a high-capacity hydrogen economy was evaluated to be strategically relevant to store off-shore wind energy in combination with advanced electrolysis technologies already in the 2004 progress report. [Bundesregierung, 2002, p. 157, 183, 199; Bundesregierung, 2004, p. 26, 174, 177, 185, 195]

The Federal **Fuel Strategy** (2004) was elaborated with significant participation of the VES. It assumed GHG-emission reductions by more efficient conventional diesel or petrol vehicles, the use of NGVs and the blending of biofuels by 2010. For 2020, the strategy confirmed the dominant role of efficient conventional diesel or petrol vehicles, the market share of CNG and LPG shall reach 5%, of biogas 2-4% and of liquid biofuels 8%. Hybrid concepts would have their market breakthrough: a million vehicles is seen as important to market penetration. **Efficient conventional drives, BtL, hybrids and hydrogen** have been evaluated as the most promising GHG-reduction technologies or fuels. [Bundesregierung, 2004, p. 188 -190]

In 2004, VES evaluated the effects of the production, distribution and use of various fuels on different interest groups (fuel suppliers, vehicle manufacturers, customer, society) by technology used for fuel production and vehicles, costs of all process components, total emission balance as well as customer and social aspects. As a result, the third VES status report advised directing R&D activities on **second generation biofuels as well as H_2FC-technology**. A fuel matrix was demanded to identify possible bridging fuels on the way to the H_2-economy concentrating on renewable energy sources. H_2 produced from fossil sources was evaluated not to reduce GHG-emissions, but to be suitable to support technology development and customer acceptance during the market preparation phase. [VES, 2007, p. 10]

In 2006, the Federal Government established with the “Nationale Innovationsprogramm Wasserstoff- und Brennstoffzellentechnologie”, **(National Integrated Hydrogen Programme, NIP)**, 2007-2016, budget 1.4 G€, the necessary basis to support H_2FC-technology. It is aimed at accelerating the market preparation for H_2FC-technologies through R&D and large demonstration projects such as the CEP. The programme is operated by **NOW GmbH (National Organisation Hydrogen and Fuel Cell Technology)** which was established in 2008. The NIP is targeted at mobile/stationary energy supply and specific market[95] applications of H_2FC-technologies. It shall, in particular, strengthen the respective supplying industry. Mobile applications include H_2-propelled (FC and ICE) cars and fleet vehicles such as buses, Auxiliary Power Units, planes as well as other railway and maritime applications. On-board H_2-storage is an important R&D topic. The thematic area of H_2-infrastructure includes H_2-production, in particular, of wind-H_2 from large electrolysers with an efficiency of more than 80%, H_2-distribution and filling are further topics.[96]

Figure 4-12: CEP filling station at Berlin Jaffeéstrasse, Total[97]

The **CEP (Clean Energy Partnership**, established in 2002) emerged from the VES as a joint political initiative, lead-managed by the German Ministry of Transport and Industry. While the VES took a more theoretical approach, the CEP puts the knowledge gained into practice. [BMVBS, 2011] CEP has three phases: During Phase I (2002-2008) the CEP tested various H_2-applications such as local H_2-production by electrolysis and reformation from LPG as well as central H_2-reformation from natural gas and distribution by truck in combination with H_2-storage and filling. In 2004, the first CEP H_2-filling station owned by Aral opened at Messedamm in Berlin. CEP Phase II (2008-2010) saw the further development of Phase I technologies and the qualification of applications in daily usage, e.g. improvement of vehicle efficiency and cold-start abilities as well as a cost reduction in vehicle and infrastructure technologies. An advanced filling station was put into operation at Holzmarktstraße in Berlin. This third CEP filling station had a mini-CHP to provide the facilities with heat and electricity gained from an H_2-fired ICE. After the withdrawal of BMW from LH_2 and ICE technology development in 2009 and the stopping of the vehicle demonstration in 2010, all LH_2-applications were dismantled.

CEP Phase III (2011-2016) focuses on market preparation by testing manifold vehicles at the customer to receive more data and to further improve vehicle efficiency, performance and reliability. New partners and regions are strengthening the partnership. In 2014, about 85 FCV were operated within the framework of the CEP. Honda and Toyota announced to add some of their new FCV-models to the fleet in 2015. [Total/Enertrag, 2012] Currently 15 H_2-filling stations are operated in Germany. Since 2012 they are supplied with “green” wind-H_2. The CEP is well connected to Berlin politics, e.g. events are regularly attended by high-ranking politicians or Ministry staff.

In 2007 in **Merseburg**, the German Federal Government enacted a very ambitious **climate protection programme**. The German government offered to **reduce GHG by 40% between 2012 and 2020**, if the EU reduces its GHG by 30% and other countries also agree on ambitious targets. **30% of the electricity shall be produced from renewable energies by 2020 (50% until 2050).** In 2007, the **Integrated Energy and Climate Protection Pro-**

95 Applications for **specific markets** are e.g. FC-hybrid systems (power of a few Watts to more than 50 kW) or are used as APU, emergency power supply, on-board electricity supply of leisure vehicles as well as power supply to work machines etc.

96 http://www.now-gmbh.de, 28.5.2012

97 https://cleanenergypartnership.de/h2-infrastruktur/cep-tankstellen/, 11.06.2015

gramme (IEKP-Integriertes Energie- und Klimaprogramm) targeted at decoupling transport volume increase from energy consumption and to **reduce transport GHG-emissions by 20% by 2020**. Germany is the only EU15-country which succeeded in reducing (-3%) its road transport CO_2-emissions between 1990 and 2010. However, Germany still has the largest share in EU15 transport CO_2-emissions (19.5% followed by France with 16.6%). [EEA, 2012, p.184; Bundesregierung, 2008, p. 86, 139-141] The IEKP shall support a solid market for innovative mobility concepts, including the market introduction of innovative propulsion systems (e.g. NIP, NEP). [BMVBS, 2009, p. 14]

The **Nationaler Entwicklungsplan Elektromobilität (NEP, National Development Plan Electromobility)** set a target to implement one million electric vehicles (EV) on the road by 2020. Thereby, Germany should become a **key market for electro mobility technology and an industrial leader** in this technology The NEP is aimed at advancing R&D and preparing a market for battery-powered vehicles (BEV, PHEV, HEV) in Germany. FCVs are excluded because they are supported under the NIP, even if they are benefitting from most of the technology developments within the NEP. The NEP is focusing on battery technology in order to maintain and strengthen global competitiveness of the German automotive industry as the battery comprises 30-40% of the added value of a BEV. At present Germany is missing a strong battery industry. [NPE, 2011, p. 5-7, 11,-13]

The **H_2-Mobility Initiative** originates from the VES. In 2009, representatives of Daimler, EnBW, Linde, OMV, Shell, Total, Vattenfall and NOW signed a Memorandum of Understanding (MoU) with the German Minister for Transport, Building and Urban Affairs in attendance. In the meantime Air Liquide, AirProducts and OMV also joined the Initiative, making it the centrepiece for the commercialisation of H_2FCVs in Europe. The H_2-Mobility initiative was transformed to a Joint Venture in 2012/13. [Williamson, 2010] The Initiative reviewed various options for building a Germany-wide H_2-infrastructure assuming the serial production of FCVs and public co-financing of further H_2-filling stations. In the following, the partners agreed on a plan for a German H_2-infrastructure network to support the commercialisation of FCVs which should start in Germany in 2015, see *Figure 4-13*. New fuelling stations shall be located primarily in “high-density” regions of Baden-Württemberg, the Ruhr area, Frankfurt area, Hamburg and Berlin as well as at corridor locations. Thus, Germany will be the first country with an area wide H_2-infrastruture. [Friedrich, 2012, p. 23-24] The network should emerge in metropolitan areas and develop via corridors into an area-wide coverage.

Due to the delayed market introduction of FCVs the development of the infrastructure is lagging behind. In 2012 Daimler, Linde, Air Products, Air Liquide and Total agreed to invest 20 M€ in a further 36 stations up to a total of 50 stations with the support of the Federal government (NIP) by 2015. [Ehret, 2012, p. 7] These construction plans are also delayed. However, recently it was announced to have about 400 stations by 2023, the first 100 of which shall be working by 2017.[98] Nonetheless, compared to the implementation of the CNG filling station network this is a very ambitious approach. The initiative is planning for an EU-wide roll out plan in co-operation with the FCH JTI and others.

[98] http://www.reuters.com/article/2013/09/30/germany-daimler-fuelcells-fillingstation, 12.02.2014

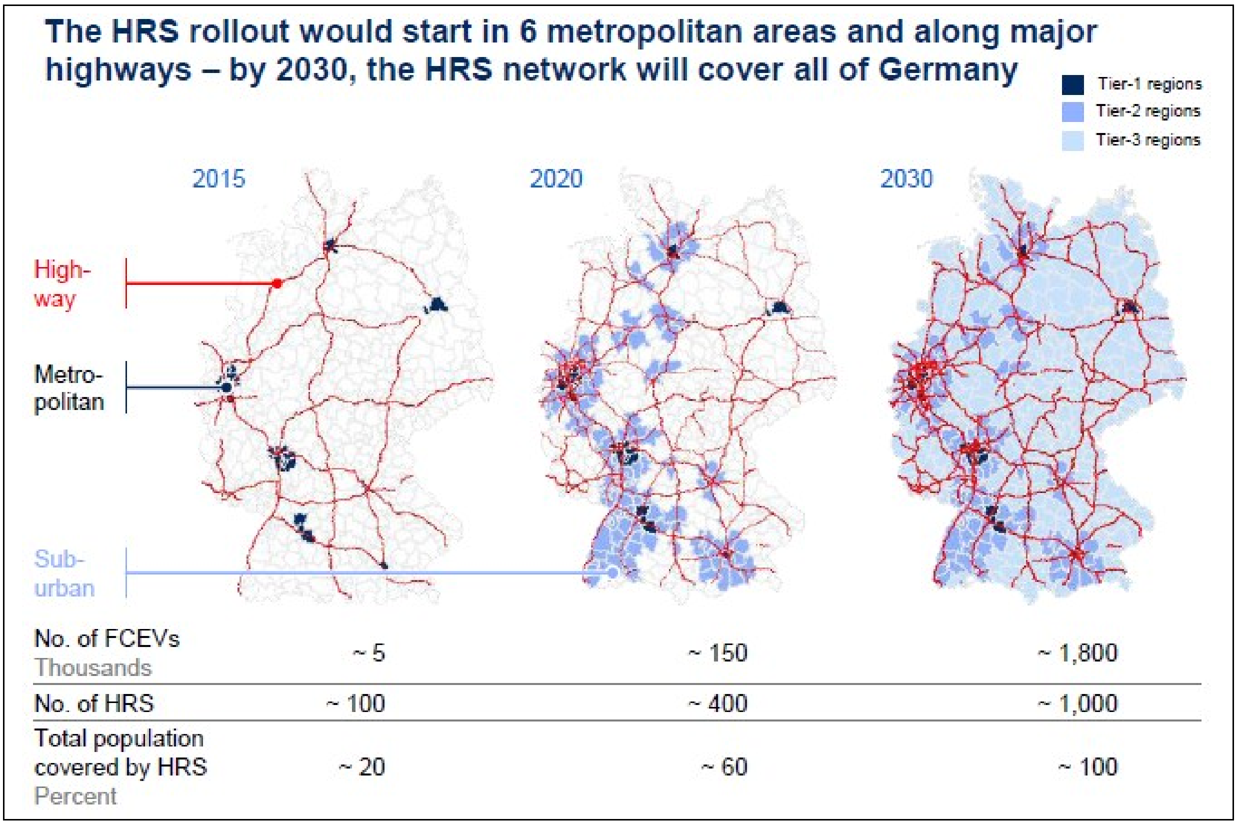

Figure 4-13: H_2-mobility initiative 2012 roll-out plan for H_2-infrastructure [Ehret, 2012, p.13]

In addition, there are several activities at local level mainly focusing on the implementation of FCVs and public transport FC-buses, e.g. **Clean Cars Initiative of the City of Hamburg** or **HyCologne**. However, the FCV- and H_2-infrastructure implementation needs a reliable investment framework. Binding instruments are still missing. Any regulation should be linked to the number of FCVs registered. A regulation comparable to the Californian Clean Fuel Outlet (see section 4.1.2), could end the wrangling between car and energy industry on responsibilities and obligations.

Following the Fukushima disaster in 2011, the German government decided to finally exit from nuclear energy and updated its energy policy accordingly. The German Energiewende is based on increased energy efficiency and a switch to RES (*Figure 4-14*).

	2020	2030	2040	2050
Reduction in GHG-emissions (reference:1990)	-40%	-55%	-70%	-80-95%
Reduction in primary energy consumption (ref.: 2008)	-20%			-50%
Reduction in electricity consumption	-10%			-25%
Reduction in final transport energy consumption	**-10%**			**-40%**
Share of renewables in gross final energy consump.	**18%**	**30%**	**45%**	**60%**
Share of renewables in gross electricity consumption	**35%**	**50%**	**65%**	**80%**
Reduction in nuclear energy	-60%	2022: -100%		

Figure 4-14: Targets of the German energy efficiency and climate policy [Nitsch, 2012, p. 2]

The "**Mobility and fuel strategy (MKS), 2013"** does not favour any technology or energy carrier, but shall support the government **in saving 10% energy in the transport sector by 2020 and 40% by 2050**. The market introduction of the first commercial FCVs is expected for 2017. A network of k1 H_2-filling stations shall be achieved by the H_2-initiative by 2030. (For comparison, the first German CNG filling station was erected in 1993.) Support for H_2FC-technology will include further public-private co-operation and continuation of R&D-activities, e.g. NIP. [BMVBS, 2013, p. 6, 76, 86] It is planned to extend the NIP beyond 2016. The new programme's content is currently negotiated, including the integration of H_2FC-technology into the Energiewende as a main pillar. Milestones until 2023 include:

- Integrate H_2FC-technology to the transport sector with more than 500 public H_2-filling stations, more than M0.5 FCVs registered and k2 FC-buses in public transport,
- Capacity of 1.5 GW H_2-electrolysers from renewable energy sources installed,
- More than M0.5 stationary FC residential heating systems in use, more than 1 GW FC CHP in operation, more than k25 FC APU systems installed.

The programme shall include co-financing for demonstration and market preparation (BMVBS, 500 M€), applied energy R&D (BMWi, 200 M€), market activation through H_2-infrastructure implementation (200 M€), backup through renewable H_2-production and storage capacities (300 M€) and FC-CHP technology introduction (400 M€), totalling 1.6 G€ public funding, supplemented by 2.3 G€ private financing. [Menzen, 2013]

In conclusion, the various national and international R&D projects have resulted in a good cooperation level between all relevant stakeholders. Only users are underrepresented due to a lack of FCVs on the market. The technical strengths and weaknesses of the technology (FCVs and infrastructure) are understood; organisational and legal hurdles for market introduction as well as further technical development needs have been identified. Individual countries have developed deployment concepts, which show different levels of stringent requirements. The Californian concept is best synchronising infrastructure and FCV-development. It sets the strictest legal requirements. Japan has a strong government programme. Consequently, Toyota is focusing its FCV launch outside Japan in California. Hyundai's new FCV model is already available in Europe, e.g. in demonstration projects in Copenhagen and the UK. Daimler is focusing on the German market. The other manufacturers have not yet published their strategies in detail.

4.2 Overview on competing vehicle technologies and fuels

FCVs will have to compete with other vehicle technologies during the marketing penetration phase and beyond. The incumbent technologies, naturally, have a very strong market position. They still have improvement potential and, in particular, in combination with biofuels, may further decrease specific GHG-emissions. Also, HEVs, PHEVs and BEVs are entering the vehicle market and have the potential to significantly reduce GHG-emissions **and** to increase energy efficiency.

4.2.1 Incumbent petrol and diesel internal combustion engines technologies in combination with first or second generation biofuels

Internal combustion engine (ICE) technology is dominating the current vehicle propulsion using different fuel feedstock. Several technologies based on ICE are currently applied or developed to improve the energy efficiency of the ICE. These measures are concentrating on engine design principles to reduce losses, i.e. exhaust and heat losses make up 62% of the fuel energy, only 38% is used as mechanical energy or energy to the piston. Measures include thermal management, friction reduction (transmission, pumping), system and after treatment optimisation, use of lightweight materials etc. In addition, drive trains are optimised including downsized turbo petrol direct injection engines, variable valves and active fuel management or direct injection diesel engines. [Brown, 2012, p. 5-6]

Also **hybridisation** reduces the fuel consumption. **Micro-hybrids** demonstrate the lowest level of hybridisation. They are typically equipped with a starter-generator-system providing at least a start-stop-functionality [Bosch, 2007, p. 747] and could be combined with regenerative braking. Bosch estimates that 90% of the newly registered vehicles will be equipped with a start-stop-functionality by 2017. Bosch quantifies the possible fuel reduction as 8% on the urban part of the NEDC. [Bosch, no year, p. 8]

The car manufacturers achieved a 27.5% reduction in the European fleet average from 182 CO_2/km to 132 gCO_2/km between 1997 and 2012. In the OECD countries, fuel efficiency increased by 2.7% p.a. without significant electrification of the drive train between 2008 and 2011. [Fulton et.al. 2014, p. 2] The future environmental and energy optimisation potential is difficult to evaluate. A draft version of the EU's Horizon2020 set the following general targets:

"Demonstration vehicles incorporating the new engine technologies must prove, by independent testing, real driving emissions at least below upcoming Euro 6 limits, targeting for the longer term the establishment of a future **'Super Low Emission Vehicles'** standard with emission targets which are ambitiously lower than Euro 6. This will help bridge the transition to zero emission vehicles in urban agglomerations. The research will verify the feasibility of these stricter limits and provide evidence in view of the development of European emission standards beyond 2017. At the same time they should demonstrate **a 15% improvement in fuel consumption for gasoline and 5% for diesel in comparison to the best vehicles on the market in 2013**." [EC, Draft Horizon 2020, 2013, p. 24]

In 2013, newly registered compact cars showed an average of 124.2 gCO_2/km in Germany. The best diesel cars achieved about 110 gCO_2/km, the best gasoline cars about 120 gCO_2/km. [kba, fz14, 2013] For a state-of-the-art car such as the Chevrolet Cruze Eco (1.4 l turbo ecotec, 127 gCO_2/km) engine improvement could lead to ca. 107 gCO_2/km, i.e. 16% improvement. [Brown, 2012, p. 4] Thus, the target is not very ambituos. However, the Toytoa Prius reached 79 gCO_2/km already in 2013. Therefore, the mid-term strategy to further fuel reduction by many vehicle manufacturers is focused on electrification of the drive train, see section 5.3.1.1, (see also *Figure 4-15*) In particular Toyota sells a high share of HEVs.

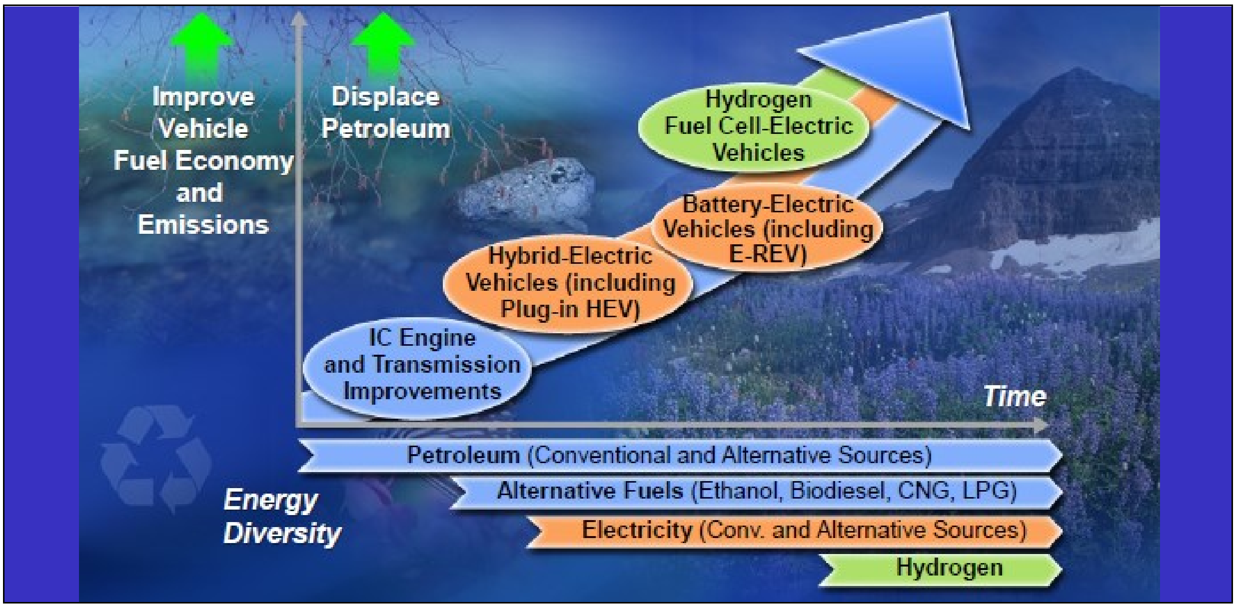

Figure 4-15: GMs advanced propulsion technology strategy to meet global efficiency criteria [Brown, 2012, p. 4]

However, the quality of the fuel also determines the efficiency and emission of the engine, i.e. the fuel sulphur content and quality of biofuels used (see section 3.2.2.). An optimised fuel would be characterised inter alia by:

- Close tolerances for the physical and chemical characteristics,
- Combustibility and knock resistance in the stipulated range,
- Clean combustion and simple exhaust cleaning, high energy storage density,
- Safe handling also by laymen and low tendency to form explosive mixtures,
- High global availability, low costs and dense filling infrastructure available,
- Non toxic, non carcinogenic, non corrosive. [Schindler, 1997, p. 7]

Diesel fulfils many of the requirements. Conventional diesel is a non-homogenous fuel (contains hydrocarbons with approximately 12–20 carbon atoms) with a broad boiling range. It has a density of 820–860 kg/m³, a lower heating value of 42.8-43.1 MJ/kg (resulting in a comparable high energy density of about 35.2 MJ/l), a minimum Cetan-number of 51, a maximum content of polyaromatic compounds of 11 mass% and of 10 ppm sulphur (EN 590). However, advanced technologies such as the application of Homogenous Charge Compression Ignition require a homogenous air-fuel-mixture and need optimised fuels, which could be produced, inter alia, through Gas-to-Liquid (GtL) or Biomass-to-Liquid (BtL).

Tailor Made Fuels (TMF) offer opportunities to reduce the GHG-emissions of both conventional spark ignition and diesel engines due to the increase of the efficiency of the combustion process. TMF could be produced from biomass or from fossil fuels (more cheaply). However, these engines are not yet available on the market, respective fuel quality standards are missing. Vehicles would need a dedicated fuel and own dispensers and tanks at the filling station. Already today many filling stations operate close to their underground tank capacity limits due to the multiple fuel grades. The readiness of politicians and the mineral industry to support the supply of TMFs is unclear, particularly after the unsuccessful implementation of E10.

The term **biofuels** describes two broad fuel qualities. In general, **first generation biofuels** are directly produced from food crops such as cereal crops (e.g. wheat, maize), oil crops (e.g. rape, palm oil) and sugar crops (e.g. sugar beet, sugar cane) using established technology. Products are:

Biodiesel (RME, Rape Methyl Ester) or FAME (Fatty Acid MethylEster) is typically produced from oil crops such as rape, palm, soy etc. European biodiesel is mainly produced from rape, US biodiesel from soy. In Germany, the former number of k1.9 German biodiesel filling stations decreased to only a few installations due to the increased taxation of biodiesel. The info service ufop.de stopped listing of filing stations.[99] First generation **bioethanol** is produced from crops such as wheat, corn, sugar cane and sugar beet. **Ethyl Tertiary Butyl Ether (ETBE)** is produced from ethanol and isobutylene in a catalytic reaction, isobutylene is currently derived from fossil sources (as a by-product of refining or from natural gas). Blending with ETBE (up to 22-Vol% [Directive 2009/30/EC]), improves the combustion characteristics of petrol and ETBE is also more compatible with pipeline and engine materials than ethanol.[100] The future use of biodiesel, ethanol and ETBE will be probably limited to blends in Germany. **Biogas** is a mixture of methane CH_4 (65-70%) and CO_2 (30-35%) and small amounts of other gases. It is produced from organic waste such as biowaste, sewage, manure, landfill, etc. This is an established technology.[101]

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99 http://www.biodiesel.org/what-is-biodiesel/biodiesel-basics, http://www.adac.de/infotestrat/tanken-kraftstoffe-und-antrieb/alternative-kraftstoffe/biodiesel/#tabid=tab2, 02.03.2014

100 http://www.biofuelstp.eu/etbe.html, 31.10.2012

101 After removal of contaminants and drying of the gas, biomethane/biogas has the similar characteristics as natural gas and can be used as a transport fuel in the form of LNG or CNG.

The world **biofuel production and consumption** has been stabilising recently (see *Figure 4-16*). Renewables provided 2.5% of the 2.377 Gtoe world's transport fuel consumption. [IEA, 2013 (2)] In 2012, the world production of ethanol was about 1.5 Mbbl/d and has more than doubled since 2006. Two countries, Brazil and the US, account for 87% of global production and 83% of the consumption of bioethanol (Brazil 25%, USA 58%).[102] Germany (27 kbbl/d), and the United Kingdom (17 kbbl/d) are the largest European consumers. However, the availability of biofuels for the use in cars may be limited because they could preferably be used in applications which maximise their GHG-reduction potential (the optimum use of renewable energy sources such as biomass and wind requires consideration of the overall energy demand, including HDVs and stationary applications).

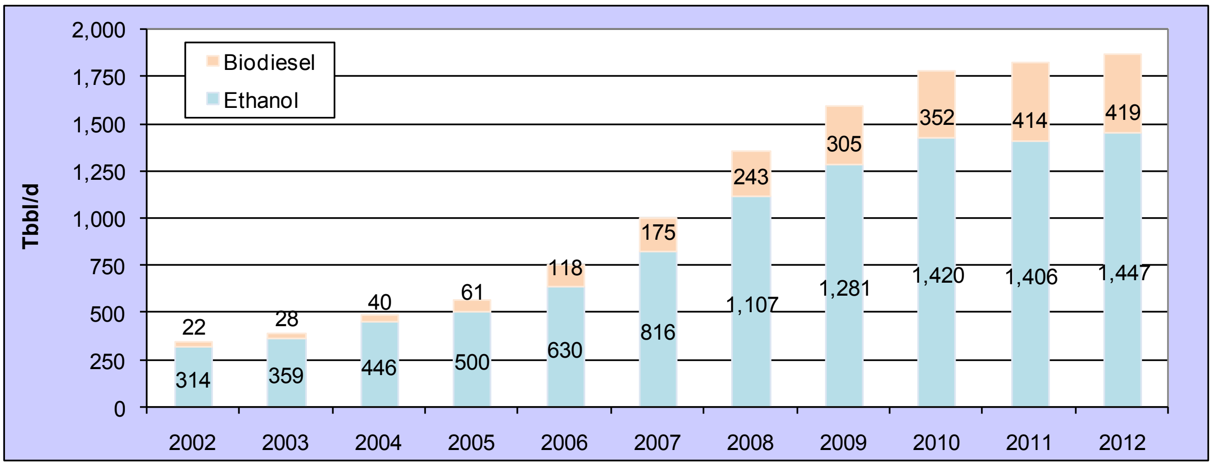

Figure 4-16: World biofuel consumption in Tbbl/day[103]

Oxfam and other organisations heavily criticised that, according to EU figures, 90% of first generation biofuels are made from food crops and this will remain virtually unchanged until 2020. Even if most of the biofuels are produced inside the EU, the evidence on the contribution of biofuel policies to recent international food price spikes was so compelling that, in 2011, ten international organisations, including the International Monetary Fund and the World Bank, made an unprecedented **call for G20 governments to scrap biofuel mandates and subsidies**. By 2020, EU biofuel mandates alone had the potential to push up the price of some foods by as much as 36%. Oxfam claimed that recent evidence suggests that two thirds of big land deals in the past ten years are to grow crops that can be used for biofuels, such as soy, sugarcane, palm oil and Jatropha. The institutional structures in developing countries furthermore contribute to an occupation of land by investors and corporations without the consent of affected communities. In addition, the huge plantations often compete for local water resources with local farmers who experience water-shortfalls as a consequence. Despite the current limitation of the EU Directive, growing crops for biofuels may also displace other agricultural production which works as 'carbon sinks', such as forests, peat lands and grasslands. [Kelly et.al., 2012, p. 2, 3]

Second generation biofuels are produced from lingo-cellulosic feedstock such as energy crops (use of the whole plant increases the energy yield per hectare), agricultural residues (e.g. straw, corn stover) or forestry resources. The sustainability of second generation biofuels is measured on a net GHG-reduction across the "value chain" (the specific combination of sustainable feedstock, conversion process and end products), with no "negative effect on

[102] http://www.eia.gov/; table: Biofuel consumption/production, 24.08.2015
[103] http://www.eia.gov/; table: Biofuel consumption, 24.06.2015

biodiversity or land use".[104] Second generation biofuels are currently in the R&DD phase. In a first step a synthesis gas of CO/H_2 (syngas) is produced. The **Biomass to Liquid (BtL)** process uses gasification to produce syngas. In a **Gas to Liquid (GtL)** process syngas is produced from methane through steam reforming ($CH_4 + H_2O \Leftrightarrow CO + 3\ H_2$) or partial oxidation ($2\ CH_4 + O_2 \Leftrightarrow 2\ CO + 4\ H_2$). In the following Fischer-Tropsch process the syngas reacts in the presence of Fe- or Co-catalysts at a pressure of 2-4 MPa and temperatures of 200–350°C forming Alkanes or Alcohols. [Unruh et.al., 2003] The Fischer-Tropsch process is a well understood, industrial process for converting syngas into liquid hydrocarbons. However, only few demonstration plants (e.g. Bioliq plant in Karlsruhe) for converting biomass to fuels exist because biomass is a heterogeneous, decentrally distributed resource with a low volumetric energy density (2 GJ/m³) and high ash content causing problems of corrosion, adhesion and clogging in the plant. In addition, the input syngas has to be cleaned. The Bioliq plant is able to produce petrol. [Karlsruher Institut für Technologie, 2013]

BioMethanol can be produced from a wide range of biomass feedstock via a thermochemical route similar to the Fisher-Tropsch-Synthesis. Methanol can be converted to **Dimethylether** (**DME**: $H_3C–O–CH_3$) by catalytic dehydration. DME is gaseous above -25°C or below 0.5 MPa, but can be liquefied at moderate pressure; a fuel for compressed ignition engines using a purpose-designed fuel handling and injection system as well as a dedicated infrastructure. It burns very cleanly and produces virtually no particulates and low NO_x-emissions. Compared with diesel, Bio-DME generates 95% lower CO_2-emissions.[105]

Cellulosic ethanol is produced from different raw materials (agricultural residues (e.g. straw, corn stover), lignocellulosic raw materials (e.g. wood chips) or energy crops (miscanthus, switch grass, etc.)). The US National Renewable Energy Laboratory (NREL) showed in a modelling approach that it is possible to produce cellulosic ethanol at 2.15 USD/gallon (0.57 USD/l) from a biochemical process platform.[106] Key challenges for biochemical conversion include cost reduction and difficulty involved in breaking down the tough, complex structures of the cell walls in cellulosic biomass and the efficient conversion of the sugars into biofuels and their purification. DOE runs two process demonstration units currently. [DOE, 2013]

Synthetic Natural Gas (SNG) and **Power to Liquid (PtL)**, i.e. the combination of H_2-electrolysis from excess wind energy (η=70%), methanation (η=70%) followed by a GtL suffers under a low overall process efficiency is low. [Mohrdieck, 2013, p. 69].

The use of biofuels is currently declining in Germany. The sustainability debate on biofuels continues: the EU announced it would resign from setting a biofuels target beyond 2020 (COM(2014)15) and even conservative organisations such as the World Bank are calling for scrapping incentives and mandates. Furthermore, second generation biofuels still lack large production plants and coherent action to build up a related infrastructure. Doubts over sustainability of biofuels (including competition for land and water) and competition with the power sector limit their market penetration potential.

4.2.2 Liquefied Petroleum and Compressed Natural Gas vehicle application

Liquefied Petroleum Gas (LPG) or autogas is a byproduct of refining of crude oil or from oil or gas streams extraction. The main components of LPG are propane (C_3H_8), propylene (C_3H_6), butane (C_4H_{10}) and butylene (C_4H_8). The mixture ratio varies throughout Europe. In Germany

104 http://www.biofuelstp.eu/fuelproduction.html; 03.02.2014

105 http://www.volvotrucks.com/SiteCollectionDocuments/VTC/Corporate/News%20and%20Media/-publications/Volvo%20BioDME.pdf, 01.11.2015

106 http://www.nrel.gov/continuum/sustainable_transportation/cellulosic_ethanol.html, 15.11.2015

the propane/propylene share is mostly 95-vol%, but during the summertime the butane share is higher. LPG is liquefied at an approximate pressure of 0.8 MPa achieving a volume reduction in 1/260 at ambient temperature.[107] This allows for a widely unlimited tank geometry. LPG has a very low sulphur content and burns nearly residue free with no carbon particulate matter emission (also no engine oil pollution occurs). LPG has a higher knock-resistance compared to petrol (ROZ of 101-111 to ROZ 98). The gas is odourless and invisible: for safety reasons, an odorous substance is added. The German 95:5 propane/propylene:-butane LPG has a density of about 0.53 kg/l, this is approximately 30% less than the density of petrol (0.75 kg/l). Its lower heating value is 23.4 MJ/l; this is only 77% of the petrol lower heating value (30.8 MJ/l). LPG is heavier than air and gathers on the floor in the event of an accident. It volatilises at a slower rate than natural gas or hydrogen.

Spark ignition vehicles may be converted to the use of LPG. LPG vehicles are normally operated in a bivalent mode which means they can change the operation mode to petrol when the LPG tank is empty. The vehicle conversion is carried out by specialist companies. The conversion costs vary between 1.9-3.2 k€, depending on the conversion kit supplier, the tank system and the vehicle type. Also, some OEMs are offering LPG vehicles which are converted directly by manufacturers or at their sub-contractors. OEM conversion has the advantage that all guarantee titles are kept.

A dense public European-wide filling station network exists compared to other alternative fuels. LPG is transported by trucks to the filling station providing more flexibility when searching for a suitable location. However, many LPG filling stations are simple selling points at propane bottlers. In Germany, there are currently more than k6.7 LPG public filling stations in operation. LPG is stored at a low pressure of 3 MPa. The LPG supply costs are small compared to CNG or CGH_2 because no compressor or compression energy is necessary.[108] The fuel costs of LPG vehicles are much lower than of petrol vehicles. The average German fuel petrol price was 1.51 €/l in 2014. The price for LPG averages 0.721 €/l (2014). Calculating an additional LPG-consumption of 20%, the fuel cost savings are about 40%. These savings are mainly due to the reduced energy tax on LPG, which accounts for only 19% of that on petrol, see section 3.3.[109] Despite the low GHG-saving potential, LPG is still named as an important future fuel option in the German sustainability strategy (see section 4.1.2). New LPG registration numbers are decreasing in Germany, see Figure 2-15. It is unclear whether car manufacturers will continue to provide LPG-vehicles or if they will focus on electrified vehicles which offer better CO_2-values. In the framework of this thesis LPG is excluded from further investigations due to the comparable low carbon advantage of current vehicle models. It is not expected that manufacturers will increase development efforts.

Compressed Natural Gas (CNG) and hydrogen are both gaseous fuels sharing a range of properties, differences in use mainly result from the different fuel characteristics (see *Figure 4-17*). DIN 51624 regulates a wide range of natural gas qualities. Methane is not a toxic gas. It is flammable and can form an explosive mixture with air. Methane itself has no odour, but natural gas is odorised for safety reason before it is distributed through the gas network. The density of methane is about half of that of air, the gas will readily dissipate into the atmosphere, if a natural gas leak occurs. CNG is stored at a pressure of 25 MPa. Naturally, the high pressure causes the gas to escape with some force so precautions are necessary. A gas leak may cause high gas concentrations to build up in the immediate vicinity of the leak.

[107] http://www.gas24.de/cms/81-0-vergleich-cng-lpg.html, 22.11.2009

[108] http://www.gas-tankstellen.de/menu.php?jump=menu; 12.04.2015

[109] https://www.adac.de/infotestrat/tanken-kraftstoffe-und-antrieb/kraftstoffpreise/kraftstoff-durchschnitts-preise/default.aspx; http://www.gas-tankstellen.de/menu.php?jump=menu, 20.07.2014

However, high gas concentrations and the tendency to dissipate upwards make it less likely for the gas in the immediate vicinity of the leak to ignite.

CNG-vehicles are equipped with safety valves, cutting the CNG-supply to the engine in case of an accident. In addition, a Pressure Relief Valve (PRV) opens when the pressure in the cylinder rises to a certain level, e.g. due to heating-up of the cylinders in the case of fire, to avoid explosion of the cylinders. The escaping gas may start burning, which looks sensational, but the flames are limited to a certain area, see *Figure 4-18*. The German automobile club ADAC carried out a crash test with two Opel Zafira. The NGV version received 9, compared to 10 points of the conventional vehicle version in the frontal impact test, because of the deformation of the passenger compartment structure due to higher vehicle weight. The test results of the lateral collision were equal. During both crash tests, the position of the CNG cylinders was not changed. The safety valves closed during the crash, thus only small gas residues from the gas system were released.[110] H_2FCVs follow a similar safety strategy.

Fuel	Methane	Hydrogen	Petrol
Symbol	CH_4	H_2	C_7-C_9 hydrocarbons, n-alkanes, isoalkane, cyclene
Molecular weight, u	16.04	2.016	
Density at 20°C, 100 kPa, kg/m³	0.6581	0.0827 LH_2 (-253°C): 70.79 g/l GH_2 (-253°C): 1.34 g/l	0.71–0.77 kg/l
Density relative to dry air	0.554	0.0696	Liquid
Diffusion coefficient, cm³/s	0.15	0.61	Liquid
Specific gas constant, J/kg,K	518.35	4,124.6	
Colour / toxicity both	none	none	yes
Odour	mercaptan	odourless	Yes
Hazards	Explosive	Highly explosive	Explosive, layering
Recommended threshold limit value	1% isolate electric, 2% remove personnel	1% increased ventilation, 2% electric shut-off, remove personnel [based on BGI 5108]	
Flammability limits in air in %	5-15%	4-74.2%	1.4-7.6%
Flame temperature, ºC	1,950	2,050	2,030
Ignition energy, mJ	0.29	0.017	0.24
Ignition temperature ºC, according to DIN 51794	595	560	220
Lower heating value	35.9 MJ/Nm³ 50.0 MJ/kg	10.8 MJ/Nm³ 8.495 MJ/l LH_2 120 MJ/kg	31.7 MJ/l 42–44 MJ/kg
Upper heating value		12.75 MJ/Nm³ 10.04 MJ/l LH_2	
Energy density, MJ/Nm³	35.882	10.783	32.8 (MJ/l)
Melting and boiling point		-259.14 / -252.87	

Figure 4-17: Fuel characteristics of methane, hydrogen and petrol [Joseph, 2009; Hedinger, 2011; SFK, 2002]

The **retail price of CNG** is fluctuating less than the price of petrol. The CNG-price varies largely at regional level: in 2013 it diverged between 0.839 and 1.250 €/kg with a mean of

110 http://www.adac.de/infotestrat/tests/crash-test/crash_gasauto/Crash_Erdgas.aspx, 6.11.2012

1.068 €/kg. This is mainly due to different pricing policies of the natural gas companies concerning the return of investment.[111] For example, the CNG-price of the filling stations in the area of the EWE in Brandenburg is normally 10 ct/kg cheaper than in neighbouring Berlin. At German filling stations, the CNG-price is indicated as price per kilogram. The German gas industry evaluates this as being a disadvantage, because the consumer cannot compare directly the energy content of CNG with that of diesel or petrol fuel.

CNG is burned in spark ignition engines, the vehicles are designed for monovalent, i.e. natural gas/biogas only, or bivalent operation, i.e. the vehicle can operate on natural gas or petrol. The first generation NGVs were converted vehicles with the CNG vessel stored in the luggage compartment. The Fiat Multipla was the first NGV on the market with under-floor cylinders (1998). Since 2001, the automotive industry started to market OEM NGVs, partly with under-floor cylinders. Only the third generation of NGVs was really developed to use natural gas in dedicated engines. In consequence, the fuel efficiency or power of the vehicles increased. The benchmark of CNG consumption is currently the bivalent VW Passat Variant TSI Ecofuel, R-Line, comprising a 1.4 litre direct injection, twin-charged engine (110 kW, 220 $Nm_{max.}$). It was designed for the use of CNG, i.e. it is equipped with hardened valves, piston rings and pistons and the air intake provides dedicated injectors to supply the gas; the resulting emission is 119 gCO_2/km. The range on CNG is about 480 km. The empty weight of the CNG-version is 1,626 kg. The comparable VW Passat TDI BlueMotion is equipped with a 77 kW, 250 $Nm_{max.}$ 2.0 litre engine, common-rail injection and an exhaust gas turbo charger, empty weight 1,547 kg. The resulting emission is 113 gCO_2/km. [VW product website]

Figure 4-18: Waste collection truck, PRVs opened due to an engine fire, gas ignited [BZ-online, 19.10.2011]

Various car models are supplied today by Fiat, VW and Opel, but also Mercedes and Audi have NGVs on offer. The CNG VW Up was top of the VCD-environmental list with an emission of 79 gCO_2/km in 2013. The industry expects several technology improvements in the next few years from new OEM NGVs, which will likely use downsized, supercharged engines; possibly combined with hybrid solutions. Furthermore, the impact of biogas can bring the CO_2-emissions down further when considering WtW-emissions. [Matic, 2009]

CNG cylinders are an important component on board of NGVs. They are available in a number of different types, weights and sizes to suit different applications. **ISO 11439** (High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles), published in 2013, defines four cylinder categories. The cylinders differ in weight and price as CNG-1 covers the cheapest and heaviest kind of cylinders and CNG-4 the lightest and most expensive. A similar nomenclature is used for H_2-cylinders. For example,

Figure 4-19: Opel Zafira with CNG storage system[112]

[111] http://www.gas-tankstellen.de/menu.php?jump=preise, 18.07.2013

[112] http://www.iangv.org/natural-gas-vehicles/vehicle-fuel-storage/, 05.11.2012

CNG-4 cylinders consists of a resin impregnated continuous filament with a non-metallic liner (all composite). They need to comply to minimum burst pressures for different types of fibre: 3.65, aramid: 3.1, carbon: 2.35. The burst pressure is defined as the ratio to working pressure.[113]

The H_2-vehicle manufacturers may learn in particular from lining the pipes and valves in the vehicle, the arrangement of cylinders in the vehicle and from CNG handling and safety procedures. The cylinder industry benefits from experience in the manufacturing processes and from practical knowledge from the transfer from single production to mass production.

Figure 4-20: Road sign

A **typical CNG station** includes a compressor, a gas dryer, storage vessels, dispensers and underground piping. Its general design resembles that of an H_2-station. The German CNG filling station network was developed in stages. In a first phase, filling stations were installed at fleet operators with a sufficient number of vehicles to utilise the station's capacity. In a second phase, small units were erected at public filling stations which were extended when demand increased. Public filling stations combine several advantages: payment with fuel or credit card is possible, the shop, tyre pressure control etc. can be used and they are usually open for a 24/7 schedule. In a third phase, a network of filling stations was created. In July 2015, 917 filling stations were in operation in Germany.[114] The "1,000 filling stations target" of the "NGV market introduction strategy" of the German gas industry which should have been reached already in 2006 is still not achieved. 1,000 filling stations are sufficient to supply one million NGVs . A natural gas pump would be available every five kilometres in cities, every ten kilometres in mixed areas and every 20 to 25 kilometres in rural areas.

The delay is partly due to the fact that the natural gas companies are normally not the owner and operator of the natural gas filling stations, but the mineral oil companies. In addition, there are still problems with the natural gas supply along highways because of a lack of natural gas pipelines in a short distance to the highways. The German Ministry for Transport incorporated an international road sign indicating the location of a natural gas filling station in the German Catalogue of Road Signs carrying the number 365-54 (see *Figure 4-20*) to allow a unified signposting of natural gas filling stations. However, the wide use of navigation systems and the availability of a CNG-filling station information in several route planning systems makes the organisation of trips easier.

The operators of the natural gas filling stations may be categorised threefold: fleet operators, large mineral oil companies and small branded as well as independent filling stations, incl. agricultural cooperatives. *Figure 4-21* depicts the development of the structure of the natural gas filling operators. There are large differences in the commitment to develop the CNG infrastructure of the groups. In 1995, thirteen CNG filling stations existed in Germany, twelve of them were in the hands of fleet operators (public bus, waste management, energy companies etc.). Only one filling station was operated by the Esso company. In 2000, 106 CNG filling stations existed (41% fleet operators, 38% large mineral oil companies, 22% small or independent operators). In 2012, 54% of the CNG filling stations were operated by large mineral oil companies (493 filling stations). Remarkably is the engagement of small companies or independent operators (351 stations, 39%). They have a regional importance or are jointly operated with agricultural co-operations. Some are located at car dealers,

113 http://www.iso11439.com/faq.php, 26.03.2009
114 http://www.gas-tankstellen.de/menu.php?jump=menu; 20.07.2015

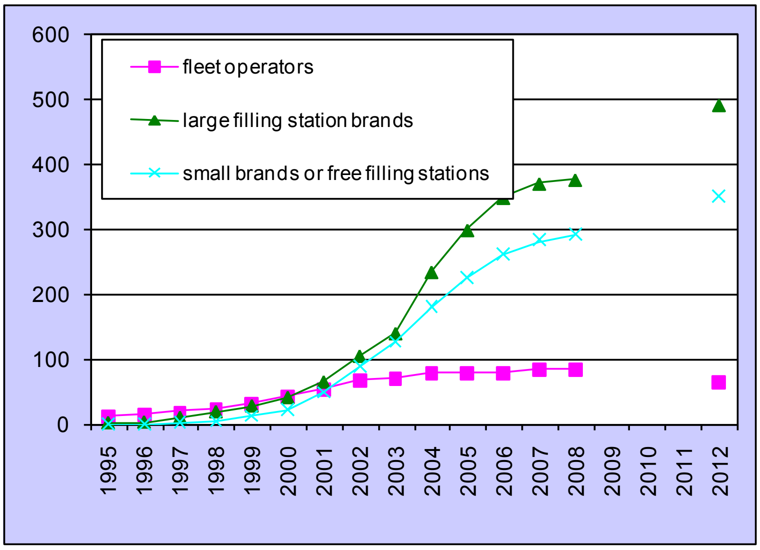

Figure 4-21: Development of the German operator structure of natural gas filling stations[116]

supermarkets, leisure parks etc. In the meantime, the fleet companies lost importance, operating only 65 public filling stations (12%). Since 2004 no new public filling station has been opened by this group. The biogas share supplied (eligible bioquota) varies according to the type of operator from 23% (fleet operators) to 13% at independent or small companies to only 9% at stations of mineral oil companies.[115] [Peters, et.al., 2011, p. 8]

The H_2-industry may learn from the experiences of the NGV industry on how to handle a gaseous fuel at the filling station safely, how to measure and invoice the fuel and on strategies to develop a filling station network. However, the CNG stakeholders also coined the phrase "chicken and egg" problem to describe the need to balance the number of filling stations and vehicles on the market. Any debate on cost sharing for the provision of the H_2-infrastructure should not be made public by the H_2-stakeholders.

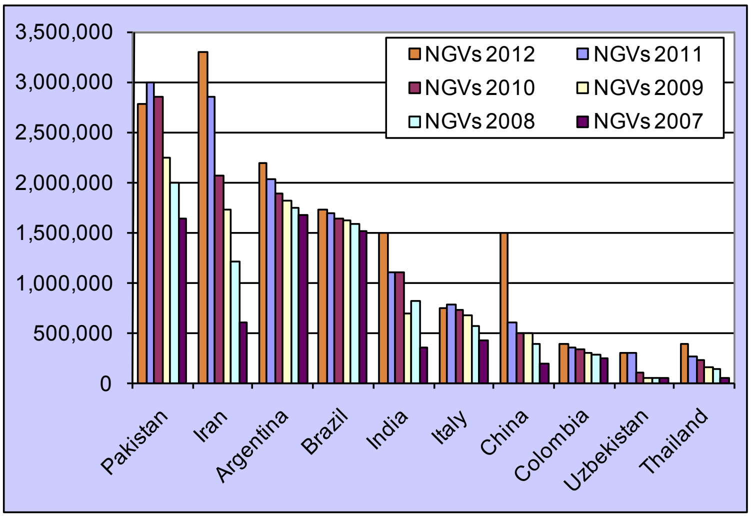

Figure 4-22: Number of NGVs on the road in different countries[117]

From mid-2013 the worldwide NGV numbers have grown from M17.2 to M19.9 NGVs (M16.4 cars, M1.35 MD/HD buses, M0.56 MD/HD trucks and M0.025 other vehicles) in mid-2014; operating in 85 countries in 3,640 cities and using 25,290 stations. The respective monthly natural gas fuel sales amounted to 2.4 GNm³ in 2014. [gvr 150, 07-2014, p. 58-62] The International Association for Natural Gas Vehicles (IANGV), a lobbying organisation established in 1986, is targeting to reach M50 NGVs on the road globally by 2020. NGVs left the air pollution niche and are making headway on economic and energy security grounds. The technology became reliable and NGVs provide solutions to a wide variety of applications. Even heavy duty applications can now rely on natural gas engines and conversions. However, growth in the sector is uneven and concentrated on specific countries and vehicle types. The highest penetration is gained in the public bus market, followed by the

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115 Own calculation, data from http://www.erdgas-mobil.de/downloads/#c4226, file: Tankstellen-_sortiert_nach_PLZ__Quartal_3_12.pdf; 07.11.2012

116 Own depiction: http://www.erdgasfahrzeuge.de/alphabetische_liste.xls; 20.07.2008

117 gvr issues 04/09, 03/09, 05/2012, 07/013, asian 03/09; http://www.ngvaeurope.eu/downloads/-statistics/20100406/5-ngvs-and-stations-worldwide-dec-2009-update.xls; http://www.ngvaeurope.eu/-downloads/statistics/20110217/5-ngvs-and-stations-worldwide-dec-2010.xls; 21.07.2013

car market. HDVs are lagging behind this development. This is in particular related to aspects of range, payload and the low filling station network density.

The world market of NGVs is heavily concentrated, because only a number of countries undertook large-scale development programs: 35% of the world fleet is located in Pakistan and Iran, another 28% in Latin America, mainly in Argentina and Brazil. (In Pakistan even the majority of private vehicles are running on natural gas.)[118] The six NGV banner nations with more than M1.5 NGVs each include also India and China. [gvr 11/2012] The global NGV numbers grow very quickly, boosted by legislation. The NGV banner countries are not typical "green countries", but emerging countries with a young population, significant motorisation rates and large metropolitan cities, but low budget for mobility and may also possess natural gas resources (Latin American countries and Iran). Conversion of cars and other vehicles is still common technology in Asia and Latin America, but OEM vehicle production is growing. OEM NGVs on offer are often dedicated for use in emerging markets and national emission standards. However, the Latin American-Asian-Pacific NGV market has only a very low impact on the European NGV market.

Germany has the second largest NGV population in the EU. The German NGV market introduction strategy is based on three steps: Firstly, introduction of NGVs was targeted at public or energy company vehicles as well as locally operating HDV and public bus fleets. The latter was aimed at better use of the capacity of the filling stations. Nonetheless, experience has shown that private cars and large bus or waste truck fleets cannot be filled to the satisfaction of all users at one dispenser. During the second strategic step regional fleet operators and highly-motivated private customers were approached. Several energy companies offered incentives on fuel costs or direct subsidies to the vehicle purchase (up to 3 k€/NGV). Promotional organisations, mostly financed by the energy companies, provide information material on NGVs, which was often not available at the local car dealers. The current third phase of the marketing strategy is target to the mass market and private car owners. *Figure 4-23* depicts the cumulated numbers of NGVs in use in Germany. It shows all characteristics of a typical S-curve (see section 5). After annual NGV growth rates of about 40% between 2004 and 2008, the number of NGVs and filling stations is stagnating.

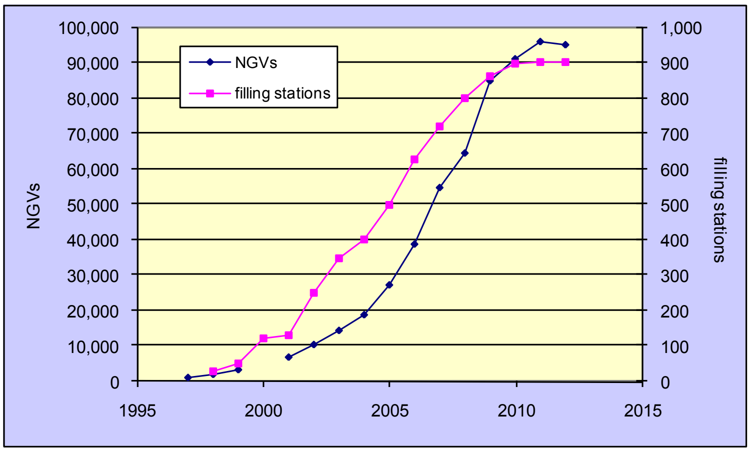

Figure 4-23: Development of number of NGVs and filling stations in Germany [gvr, various issues]

The share of NGVs of newly registered cars has decreased from 0.4% in 2007 and 2008 to less than 0.2% during recent years, despite the large improvements in vehicle efficiency, range and interior space as well as the provision of several new NGV models to the market. The vehicle numbers are still too low to allow sufficient economic operation of many filling stations. Furthermore, the network is not dense enough, in particular on highways, to allow the market to stabilise without any public subsidies. Also, vehicle sales do not cover investments by the car industry in NGV technology development. Internal meetings of the stakeholders are increasingly characterised by frustration about the low success at the market.

118 http://www.papg.org.pk, 23.03.2009

4.2.3 Hybrid, plug-in and battery electric vehicles

From today's viewpoint the future vehicle will be electrified to a greater extent. **Hybrid systems** include at least two different energy converters and two different energy storage systems for traction purposes (IEC/TC69). [Braess, et.al., 2005, p. 126] In this thesis, hybrid systems are defined as having an additional electrical power of more than 5 kW_{el}, thus micro hybrids have been classified as an energy efficiency measure under the conventional ICE (see section 4.2.1). HEVs, PHEVs, REVs and BEVs (see below for definitions) will be important competitors for FCVs. Most electrified vehicles are using batteries as an energy storage system, some ultra-capacitors. A secondary battery is a device that converts chemical energy into electrical energy and vice versa by a galvanic cell. The basic requirements for all batteries of higher electrified vehicles are as follows:

- Low costs and adequate durability resulting in TCOs to be comparable to conventional vehicles, this includes low maintenance efforts and costs,
- A battery ready for market should allow for 15 years of operation or 0.3 Mkm; these are approximately k2 to k3 BEV-charge cycles. The battery is considered to be a total breakdown when 20% of the 'Beginning of Life' capacity has gone.
- Low self-discharge rates (less than 5% per month),
- Acceptance of harsh operating environments, i.e. withstanding shock, vibration, wide temperature ranges (-30°C to +65°C) and abuse,
- High energy and volumetric density, low weight, ruling out Lead acid batteries,
- Suitable protection circuits and high (intrinsic) safety level. [Heymann, 2009, p. 6]

Hybrid and electric vehicles work with high voltage battery packs that consist of individual modules and cells organised in series and parallel. A cell is the smallest, packaged form a battery can take and generally provides one to six volts. The battery management system ensures the safe and reliable function of cells and packs. Current, voltage, temperature, insulation resistance and other variables for cells and pack are monitored and managed. Each cell has a slightly different capacity due to manufacturing tolerances and environmental conditions during charge and discharge cycles. A cell balancing system keeps all cells at the same **State of Charge (SOC)** optimising charge and discharge of every single cell in the module and thus increasing system performance, lifetime, reliability and safety. The battery management system also prevents overdis-/charge of the cells. Different variables characterise battery operating conditions and could be used to compare the specifications of various manufacturers' batteries. However, no international nomenclature exists for cells using different systems. DIN SPEC 91252 'Electrically propelled road vehicles – Battery systems – Dimensions for Lithium-Ion-Cells' shall at least allow the interchangeability of different battery systems, but is badly accepted by the car manufacturers.

Traction batteries are classified according to their storage specifications. Batteries, even batteries of the same chemistry, can be either **high-power** (HEV application) **or high-energy** (BEV-application). The BEV battery operates down to a deep **Depth of Discharge (DOD)** for long range whereas the HEV operates at a shallow DOD for long life. Batteries are made from many different types of materials enabling for different energy to power ratios. Typically, an increase in specific energy correlates with a decrease in specific power. Today Li-ion batteries have an energy density of 0.1 kWh/kg, a value of 0.2 kWh/kg is envisaged. During the last 15 years an annual improvement of 5% could be observed. With this learning rate it would need another 15 years to achieve that goal. In any case, no battery will reach the energy density of diesel which is about 12 kWh/kg. The battery capacity restricts the application area to short trips, in particular, when considering that other electricity consumers such as heating, air conditioning, radio and lighting also have to be supplied. In addition, performance must be delivered within a wide range of temperatures. [Heymann, 2009, p. 6]

Most EV-batteries are made from nickel-metal-hydride (NiMH) or with increased importance Lithium-ion (Li-ion) batteries. There exist several Li-ion chemistries, see *Figure 4-24*.

Company	Cathode	Anode	Electrolyte	Casing	Structure	Form
Toyota	NCA	Graphite	liquid	metal	wound	prismatic
Panasonic	NMC	Blend	liquid	metal	wound	prismatic
JCS	NCA	Graphite	liquid	metal	wound	cylindrical
Hitachi	NMC / LMO	Hard Carbon	liquid	metal	wound	cylindrical
NEC-Lamilion	LMO / NCA	Hard Carbon	liquid	pouch	stacked	prismatic
Sanyo	NMC / LMO	Blend	liquid	metal	wound	cylindrical
GS Yuasa	LMO /NCA	Hard Carbon	liquid	metal	wound	prismatic
A123	LFP	Graphite	liquid	metal	wound	cylindrical
LG Chem.	LMO	Hard Carbon	gel	pouch	stacked	prismatic
Samsung	LMO / NMC	Graphite	liquid	metal	wound	cylindrical
SK Corp.	LMO	Graphite	liquid	pouch	wound	cylindrical
EnerDel	LMO	LTO	liquid	pouch	wound	prismatic
AltairNano	NMC / LCO	LTO	liquid	pouch	stacked	prismatic

Figure 4-24: Material combinations of various HEV battery designs [Tübke, 2013, p.19][119]

Currently, patents for different battery chemistries are held by rival companies undertaking competitive developments with only a few signs of industry standardisation or adoption of a common product. Furthermore, many variations of the basic Lithium chemistry have been developed to optimise the cells for specific applications or to get around the patents on the original technology (see Figure 4-25 for the trade-offs of the principle Li-chemistries). For example, the use of Lithium Iron Phosphate chemistry is the subject of patent disputes. Some patents have already expired, e.g. the original patent on Lithium Cobalt technology which is perhaps one explanation for its popularity. Also, Lithium Titanate Spinel is public domain technology. [http://www.tenergy.com/Newsletter-06-18-2011]

Thermal runaway is the main safety concern. It is a positive feedback loop whereby chemical reactions triggered in the cell exacerbate heat release, potentially resulting in a fire. It may be caused by an overcharged battery, too high discharge rates, short circuits or damaged cells. Li-ion chemistries which are prone to thermal runaway, such as Lithium-Nickel-Cobalt-Aluminium, Lithium-Nickel-Manganese-Cobalt and Lithium-Manganese-spinel have to be used in conjunction with system-level safety measures such as a robust battery case, cell charge-discharge balancing, monitoring and very efficient cooling systems to prevent the early stages of thermal runaway as soon as possible. In contact with air, in particular when the melting point is reached, metallic Lithium ignites easily. It is not possible to extinguish a fire using water or foam. Contact with water causes a heavy reaction. Fire fighting with sand may stop the fire, but not the thermal chain reaction; special extinguishing agents exist to fight metal fires. Electrified vehicles should be marked on public roads. The high voltage[120] cables of electrical vehicle have an orange insulation. Rescue cards provide information to

[119] Nickel Cobalt Aluminum (NCA), Spinel-based Lithium-ion (LMO), Lithium Iron Phosphate (LFP), Cobalt-based Lithium-ion (LCO) and Nickel Cobalt Manganese (NCM)

[120] According to BGI/GUV-I 8686 DC voltage between 60-1,500 V and AC voltage between 30-1,000 V is defined as high voltage.

the action forces on the type of the vehicle, safety and rescue implications, e.g. the location of the battery and the high voltage connections. In the event of an accident, the high voltage circuit of the vehicle needs to deactivate immediately and automatically.

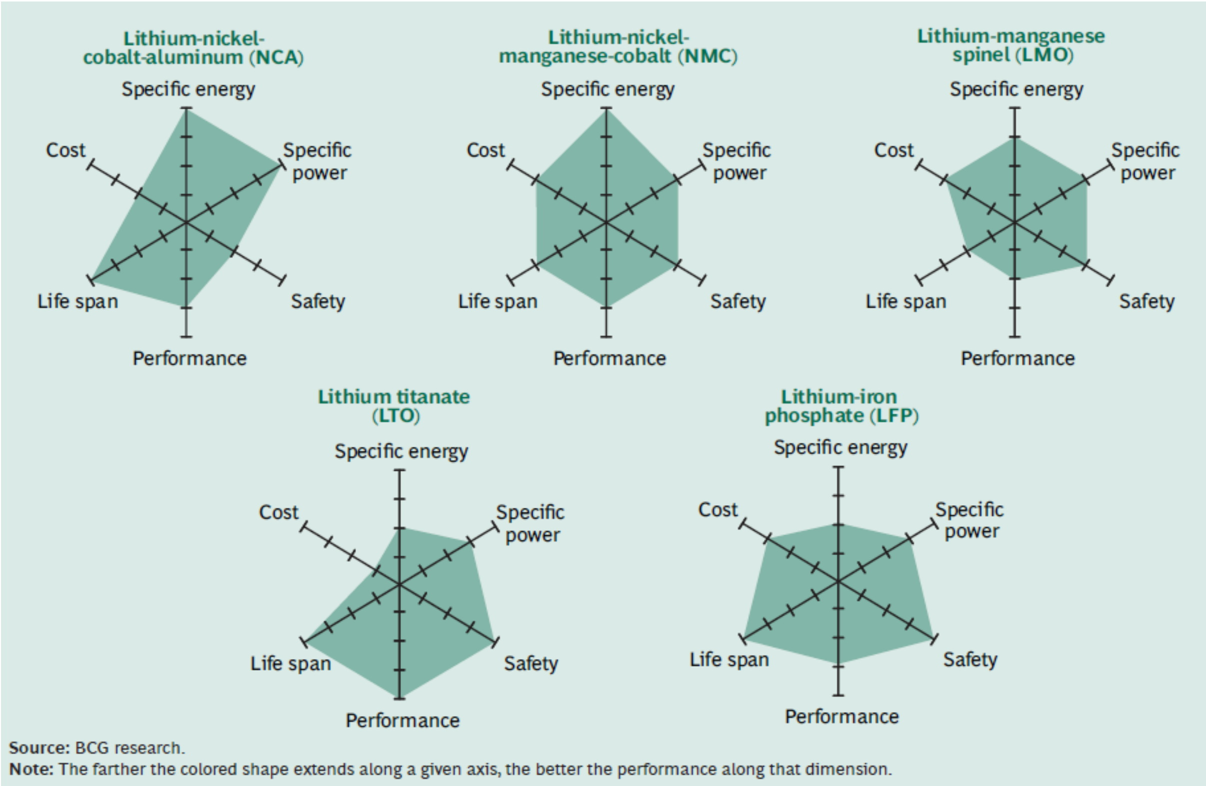

Figure 4-25: Trade-offs between the five principal Li-Ion battery technologies [Dinger, et.al., 2010 , p. 3]

In 2010, the United Nations adopted the first international regulation on the safety of both fully electric and hybrid cars. "**Regulation No 100 of the Economic Commission for Europe of the United Nations (UN/ECE) - Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train"** to ensure that cars with a high voltage electric power train are as safe as conventional cars. The Regulation also defines requirements on the practical use of electric cars, such as giving an indication to the driver that the electric engine is switched on. It also requires safeguards to prevent electric vehicles from moving when being charged. The Regulation was agreed within the framework of the 1958 UNECE agreement, so that car manufacturers are able to sell their vehicles globally on the basis of common standards. The EU incorporated the UNECE Regulation within their respective rules on technical standards for vehicles. [UN/ECE, 2012]

In 2009, the costs for the OEM were about 650-790 USD/kWh (battery); a 15 kWh-system was about 990-1,220 USD/kWh. [Dinger et. al., 2010 , p. 6; Heymann, 2009, p.5-7] Today, Tesla is probably buying battery cells from Japanese manufacturers for 150 USD/kWh, thus costs fall faster than expected.[121] McKinsey[122] expects that component costs will decrease by 80%

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121 http://reneweconomy.com.au/2014/small-scale-battery-storage-costs-tipped-to-fall-quickly-34165; 05.05.2014

122 The McKinsey study investigated technical and costs aspects of BEVs, PHEVs and FCVs in a fact-based scenario analysis on the behalf of many of the main stakeholders of the H_2FCV-technology. The information and conclusions contained in the document represent the collective view of the working groups using confidential and proprietary in-house company data in a large scale. The underlying set of proprietary data in 2010, 2015 and 2020 forms a broad range, which is normal for an industry that

by 2020 (assuming a total production of M3 BEVs in the EU). Cost reduction is achieved through improvements in production engineering (electrode cutting, forming, stacking and contacting of the collectors through the introduction of advanced laser technologies) and a shift from “batch to continuous” production modes, see *Figure 4-26*. Automation and streamlining of quality tests along the production line is another element to decrease costs. The battery is the far most expensive part of the BEV. Its life-time defines the operation time of the BEV. Li-ion batteries age with time and the number of charge cycles.

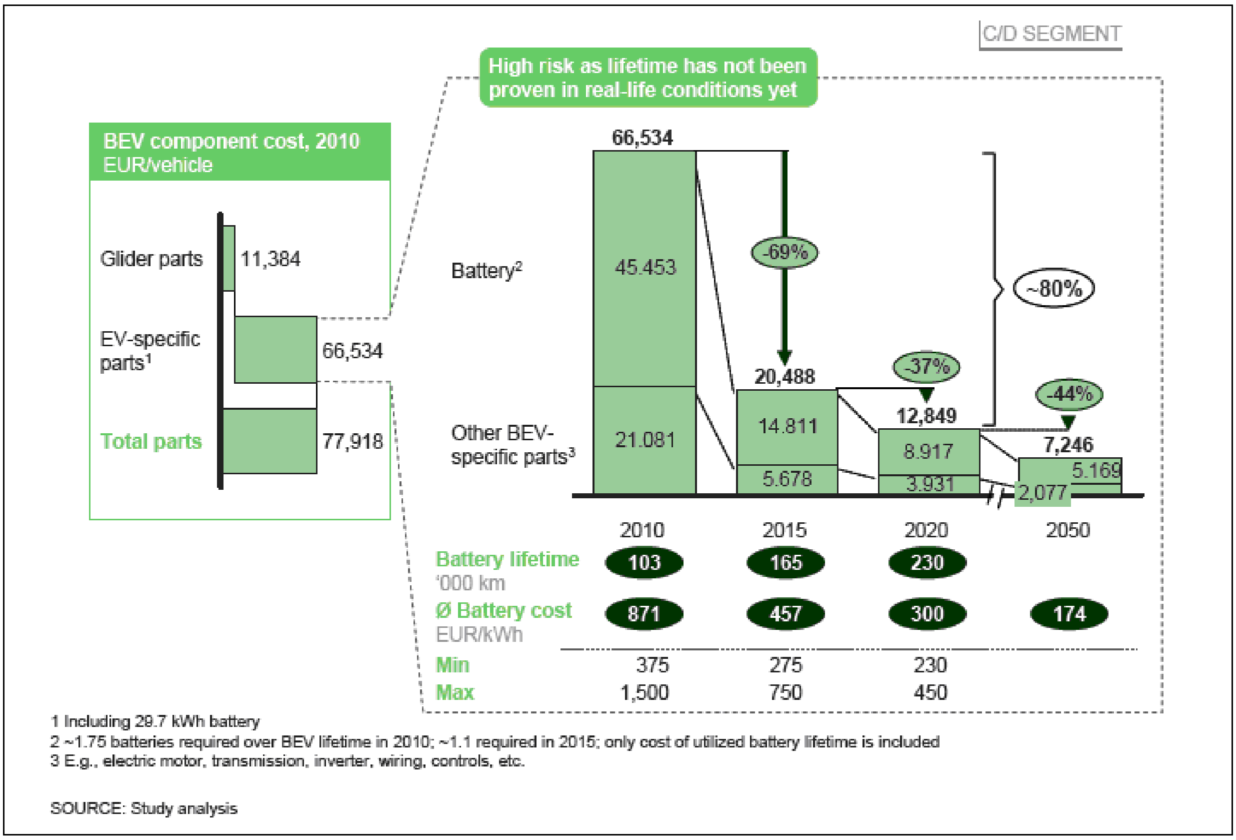

Figure 4-26: Cost development of BEV components by 2020 [McKinsey, 2010, p. 35]

In **mild hybrids** the ICE is supported by an electric engine with a power of up to 20 kW (parallel hybrid concept). It includes start-stop, boosting, brake energy recuperation and may allow for a limited electrical driving when combined with cylinder deactivation. [Bosch, 2007, p. 747] In a mild HEV, a smaller, more efficient ICE can be used without compromising too much on performance. When coasting and braking, the electric motor turns into a generator, storing energy for later use, e.g. in a battery with a capacity of more than 1 kWh, 42-150 V. Due to the absence of large battery packs and electric motors, mild HEVs are relatively easy to produce. They bear extra costs of about 2.1 kUSD. HEVs usually abstain from a conventional starter or an alternator to reduce costs, the 12 V power system is supplied

has just started mass production. The difference between the best and the worst cost data point can vary by a factor of three. Participants include:
Car manufacturers: BMW AG, Daimler AG, Ford, General Motors LLC, Honda R&D, Hyundai Motor Company, Kia Motors Corporation, Nissan, Renault, Toyota Motor Corporation, Volkswagen; **Oil and gas**: ENI Refining and Marketing, Galp Energia, OMV Refining and Marketing GmbH, Shell Downstream Services International B.V., Total Raffinage Marketing; **Utilities**: EnBW Baden-Wuerttemberg AG, Vattenfall; Industrial gas companies: Air Liquide, Air Products, The Linde Group; **Equipment car manufacturers**: Intelligent Energy Holdings plc, Powertech; **Wind**: Nordex; **Electrolyser companies**: ELT Elektrolyse Technik, Hydrogenics, Hydrogen Technologies, Proton Energy Systems; **Non-governmental organisations**: European Climate Foundation; **Governmental organisations**: European Fuel Cells and Hydrogen Joint Undertaking, NOW GmbH

using a bi-directional DC/DC-transformer. The battery operating schedule normally includes one deep discharge followed by intermittent high current charges and no prolonged operation with deep SOC. High energy throughput and high lifecycles are essential, especially if a start-stop function is used. [Book et.al, 2009, p. 3] The Honda Civic Hybrid, first launched in 2003, applies a mild hybrid function. The 2012 model includes a 15 kW electric motor supplementing the ICE (73 kW, 1.5 l four cylinder) and restarting the ICE after stops. The CO_2-emissions are: 128 gCO_2/km (5.4 l/100 km), i.e. 6.6 l/100 km for urban and 4.7 l/100 km for extra urban driving.[123]

Full-hybrid electric vehicles (HEV) are equipped with at least one high-performance electric engine with a power of 20-50 kW, which works in combination with the ICE. It allows the vehicle to be driven solely electrically. The braking energy is recuperated in a high voltage battery (>60 V). Most FCVs are also designed as hybrid vehicles, see section 4.2.4.5. Three different basic hybrid concepts exist. The ICE is configured according to the strategy of the selected hybrid powertrain structure.

In a **serial hybrid vehicle**, the ICE is not connected mechanically to the driven wheels. It is operated in a range of high efficiencies to propel the first electric motor, always working as a generator. Energy is stored in the battery system. The second electric motor is the traction drive. The ICE, the electrical generator and the traction motor have to be designed according to the continuous maximum velocity required. Both electrical motors need to be designed according to the required peak acceleration, too. This concept has the highest summarised capacity and the respective cost disadvantages. The overall efficiency of the system is calculated from the ICE via the whole electrical efficiency chain. Serial hybrids are mainly applied in buses and heavy dumpers. [Braess et.al. 2005, p. 128]

In a **parallel hybrid system**, both the engine and/or the electric motor provide power to the wheels. Therefore, various battery configurations are possible to satisfy different operating conditions. The load share of the electric motor can range from zero to 100% depending on the operating conditions and the design goals. The battery capacity may be as low as 2 kWh, but it must deliver short duration power boosts requiring very high currents of up to 40C for acceleration and hill climbing.

Mixed or power split hybrid systems are a combination of a serial and parallel hybrid system with manifold design options. In general, the ICE is used directly to propel the wheel in the efficient parts of its operating map. Power shift allows for continuous variable transmission. Toyota uses the split hybrid system in its Yaris, Prius and Lexus. For example, the Toyota Yaris includes a 144 V NiMH battery, 45 kW electric motor, 55 kW ICE, totalling 74 kW. The premium price over the basic version is 5 k€ or less than 2 k€, if an advanced transmission and other features are included in the conventional drive. The CO_2-emission is 79 gCO_2/km, the gain is 31 gCO_2/km.[124] Peugeot offers a diesel HEV (120 kW, 27 kW_{el}, 85 gCO_2/km) with a premium price of about 4 k€ and an emission gain of 54 gCO_2/km compared to a conventional vehicle. [http://www.peugeot.de/, 09.03.2014]

Plug-in Hybrid Electric Vehicles (PHEVs) are designed to be used both as a BEV for city driving and as an HEV when the charge is depleted or for highway driving. PHEV batteries must satisfy conflicting performance requirements. The recently introduced Toyota Prius Plug-in combines a 1.8 l, 74 kW engine, a 59 kW electric engine and a Panasonic 5.4 kWh Li-ion battery to drive up to 20 km electrically. [http://www.toyota.com/prius-plug-in/, 09.03.2014]

[123] [http://www.greencarreports.com/news/1069878_2012-honda-civic-hybrid-greencarreports-best-car-to-buy-2012-nominee; http://www.honda.de/automobile/modelle_civic_technische_daten.php, 05.03.2012]

[124] http://www.toyota.de/cars/new_cars/yaris/index.tmex, 09.03.2014

Range Extender Vehicles (REV) operate as a BEV until the plug-in battery capacity drops to a predetermined threshold from full charge. From there the ICE powers an electric generator to extend the vehicle's range if needed (serial hybrid). Regenerative braking contributes to the on-board electricity generation.

The full **Battery Electric Vehicle (BEV)** depends solely on electricity from the grid, which is stored in a battery, today commonly Li-ion batteries. The battery is therefore the core component of the BEV defining its future market perspective. Since 2006, a consortium of Chrysler, Ford, GM and DOE (United States Advanced Battery Consortium) has been working on the battery development for EVs (see *Figure 4-27* for the main development targets).

DOE Goals	HEV 2010	PHEV 2015	BEV 2020
Cost [USD/system]	500-800	1,700-3,400	400
Performance Discharge Power [kW] Available Energy [kWh]	 25-40 0.3-0.5	 38-50 3.5-11.6	 80 30-40
Life cycles	k300 *(shallow)*	k3-5 *(deep discharge)*	750 *(deep discharge)*

Figure 4-27: USABC targets [Snyder, 2012, p.2]

The central problems of BEV operation are range and charging. Vehicle owners with no access to a private charging point, or who are circulating further than their battery capacity allows, need public charging opportunities. Only in 2014, the EC legislative bodies agreed on the Type 2 plug (Menneke: connecting both BEV and infrastructure, one-phase/230V, three phase/400 V, 3.7-43.5 kW) as the standard European plug. However, real-world charging stations still have communication problems, e.g. different charging rates are required for different vehicle brands. Home charging at simple sockets remains difficult. For example, the Renault Zoe offers an emergency charging cable for a domestic power socket (price 599 €) only since 2014. The warranty of the Toyota PEV is void, if an extension cable is used. Outdoor-based charging requires handling of an often dirty charging cable.[125]

Today, no reliable public infrastructure for charging BEVs exists. There is also the time element to consider; recharging a battery can take from 3-8 hours, assuming a conventional plug-in to the electric grid. Fast charging may become widespread, but the impact on battery performance degradation over time and power grid stability is unclear. Additionally, communication protocols between vehicles and charging stations are not standardised yet. Moreover, it takes 15-30 minutes to (partially) recharge the battery. Fast-charging equipment is still in the state of technology development, the level of standardisation is low, demonstration systems are available for 25-30 k€. Battery swapping would reduce refuelling time, but requires at least that battery standards would be adopted by a majority of car manufacturers. Anyhow, a viable business concept suitable for the German market conditions would be necessary. In addition, the erection of charging points lacks a coherent strategy. Depending on the local circumstances, the attitudes of the municipality, of the civil engineering departments and the energy suppliers differ widely. A multitude of charging concepts are currently emerging which are not linked by a common accounting settlement system. Nevertheless, the German Energy Management Law (Energiewirtschaftsgesetz) guarantees every end consumer, including charging points, a non-discriminatory access to the electricity network. The development of the charging infrastructure, including billing procedures and charging duration is unclear yet.

BEVs would have to be introduced onto the market as part of an overall transport and energy concept rather than a stand-alone technology to become successful. If millions of BEVs

125 http://www.heise.de/autos/artikel/EU-einigt-sich-auf-Norm-Ladestecker-fuer-E-Autos-2155999.html, 15.11.2014

would be connected to the electricity grids without a negative impact, there must be an integrated approach to balance supply and demand and to ensure the use of green electricity sources. Otherwise, the anticipated increase in peak load demand would require new investments in electricity generation and grid capacity. However, the grid operator who provides the vehicle-to-grid-connection interface in an i.e. smart grid is not the seller of electricity. Furthermore, the current electricity prices and the turn over from a charging point do not allow to achieve a return of the investment soon. In addition, charging points in the public area will face a lot of problems from vandalism, long-term parking customers etc. Concepts to integrate BEVs as an inherent part of the electricity supply and distribution system are still under discussion. In that way, BEVs would not only run on green electricity, but may perhaps be used to store and supply electricity back to the grid when needed.

4.2.4 Hydrogen fuel and vehicle application

Hydrogen can play an important role by replacing imported fossil fuels currently used in cars. FCVs operating on hydrogen derived from renewables such as wind, solar energy or biomass can mitigate energy and environmental issues connected to the use of individual transport - providing their mass-commercialisation. In addition, hydrogen used to store energy can support the change in the energy systems towards clean and locally produced energies.

4.2.4.1 Hydrogen characteristics and safety issues

The use of hydrogen as a fuel results in risks to the public, but this is the case when using any combustible material. Currently, H_2-use is predominantly limited to highly trained individuals. This is due to the areas of application, not necessarily due to the risk when handling hydrogen. Nevertheless, if it is to be used in public, untrained people must be able to handle hydrogen with the same degree of confidence and with no more risk than conventional fuels. [Alcock et.al., 2001, p. 6] The basic prerequisite is the understanding of the most important risks related properties of hydrogen, in particular as the character of hydrogen differs from other fuels quite strongly, which could be harmful, but also favourable, depending on the situation. Safe handling of hydrogen could be guided through norms and standards which are already in place (see section 3.4).

Hydrogen is the first element of the periodic system of the elements; the symbol H and the atomic number 1 are assigned to hydrogen. Hydrogen is the lightest element with an average atomic weight of 1.00794 u. Its monatomic form (H_1) is the most abundant chemical substance. Nevertheless, naturally occurring atomic hydrogen is rare in the lower atmosphere ($5*10^{-5}$ Vol.%) of the Earth because hydrogen readily forms covalent compounds with most elements, it is present in the water molecule and in most organic compounds. [Hollemann et.al., 1985, p. 252] Data on H_2-characteristics are summarised in *Figure 4-17*.

At standard temperature and pressure (T = 273.15 K; p = 0.101325 MPa), hydrogen is gaseous and occurs in its stable, molecular form (H_2). Molecular hydrogen is a colourless, odourless, tasteless, non-visible, non-toxic, non-irritating, highly volatile and highly combustible diatomic gas. Due to its very low molecular mass (2.02 g/mol compared to 28.96 g/mol of air) escaping hydrogen mixes very quickly with the surrounding air. The highest flame temperature of hydrogen reached in a stoichiometric mixture with air is about 2,050°C, on the same level as a methane or propane flame. An H_2-flame radiates mainly in the UV-spectrum, thus the flame is nearly invisible in daylight; in the dark hydrogen burns with a blue flame. Due to the low radiation in the infrared range heat radiation is barely recognised. This is in strong contrast to the burning of carbon or sulphur containing fuels.

Hydrogen has a wide explosive range of 4 to 74.2% in air. The detonable range lies between 18.3 and 59% in air. An explosive mixture is hardly formed outdoors. Indoors, escaping hydrogen may form an explosive mixture, preferably under the roof.

The prerequisites for an explosion[126] are contact with oxygen and a minimum ignition energy of 0.017 mJ, which is low compared with other fuels (factor ten compared with methane and petrol). Furthermore, the laminar flame velocity of hydrogen is quite high (2.4 m/s in a stoichiometric air-mixture and a maximum of 3.6 m/s at a 40-vol% H_2-mixture) compared to other hydrocarbon fuels (ca. 0.5 m/s). In practice, a turbulent flame expansion occurs with which much higher velocities. [Air Liquide, 2012; Joseph, 2009; SFK, 2002, p. 10-12]

Figure 4-28: Burning fuels [Müller-Syring, 2010, p. 40]

Figure 4-28 shows the burning leakage of a CGH_2-tank (left side, through a valve, mounted in the boot panel). The tank is emptied within minutes. For comparison, the burning leakage of a petrol tank with fuel concentrating on the floor is shown on the right side. The hydrogen flame extension is much more limited. [Müller-Syring, 2010, p. 40] The U.S. Department of Transportation - National Highway Traffic Safety Administration carried out extensive studies on the safety of H_2-vehicles, see NHTSA, 2010. The German accident insurer DGUV advises rescue teams to use a thermal camera or a simple broom to detect an H_2-flame in the case of an accident. Firexplo, a safety consultant, conducted several tank rupture tests, see Zalosh, 2007. FCVs are equipped with H_2-sensors in the FC-system and the vehicle compartment to prevent any accident. Alarm levels orientate at the Lower Flammability Limit (LFL) of hydrogen of 4%. For example in the FC Ford Focus H_2-sensors alarm levels were set between 12.5% and 50% LFL. At 50% LFL the H_2& HV (High Voltage) systems are shut-off.

Figure 4-29: Fire at the FC ferry boat "Alsterwasser"[127]

FCVs include leakage proofed H_2-fitting technology. A crash sensor opens the shut-off tank valves and HV-circuit in case of an accident. The HV-system is disabled at ignition key-off. An additional HV main switch is installed to de-energise the system. Refuelling is only possible at ignition key-off, the vehicle starting is not possible at service (refuelling) connection. The PRV opens at excessive temperature (depending on cylinder material, e.g. >109°C) or at over-pressure of the H_2-cylinders. The vehicle H_2-fuel system is designed according to (package), safety, functionality and customer requirements. [Krüger, 2006, p. 15-17] For example, an accident happened on the MS Alsterwasser, an FC-demonstration ship, in Hamburg in 2010. During a test run of Pb-gel-batteries a fire was caused. It destroyed the FCs, but no damage occurred to the H_2-storage tank stored elsewhere.

126 Chemical explosions are characterised by the expansion velocity: deflagration 0.1 to 1 m/s, explosion 1 to 1,000 m/s, detonation more than 1,000 m/s. [http://www.stefan-lichter.de/expl.pdf; 07.11.2012]

127 http://www.abendblatt.de/hamburg/polizeimeldungen/article1476205/Feuer-auf-Alsterdampfer.html#, 24.11.2012

4.2.4.2 Hydrogen production

The use of renewable energy sources will significantly increase during the coming decades. Renewable energies have manifold manifestations such as electricity gained from hydro-, solar- or windpower, biogas or biomass. For use in the transport sector, these energy sources need to be transformed to vehicle fuels, e.g. hydrogen or are stored in batteries.

Today, the chemical industry is the largest H_2-producer and consumer in Germany. H_2-consumers are synthesis of ammonia and methanol, hydrogenation and cracking of heavy fuel oil as well as metallurgical reduction processes, use as gas for welding and cutting. H_2-production sources are natural gas reforming (ca. 6 GNm³/a), byproduct of petrol reforming (ca. 2.5 GNm³/a), byproduct of ethylene production (ca. 3.6 GNm³/a), Chlor-Alkali-Electrolysis (ca. 0.9 GNm³/a) and gasification of coal (2.1 GNm³/a). [http://www.brennstoffzelle-nrw.de/wasserstoff/erzeugung/, 15.11.2015]

US DOE set cost targets for H_2-production and dispensing taking into consideration a range of assumptions on FCVs' competitiveness compared to HEVs, a range of petrol prices and fuel economies; targets should be achieved gradually. Main cost targets are:

- **Central** H_2-production from **water electrolysis** using renewable power: 3 USD/kg at plant gate by 2015 and ≤ 2 USD/kgH_2 by 2020. **Distributed** H_2-production from **water electrolysis**: <2.30 USD/kgH_2 (≤ 4 USD/kgH_2 delivered and dispensed) by 2020.
- **Distributed** H_2-production from **biomass-derived renewable liquids**: <USD 2.30/kgH_2 (≤USD 4.00/kgH_2 delivered and dispensed) by 2020. H_2-production from **biomass gasification**: ≤USD 2.00/kgH_2 at the plant gate by 2020.
- Develop advanced **photo-electrochemical** and **biological H_2-generation technologies** with a projected cost of 4 USD/kgH_2, respectively 10 USD/kgH_2 at the plant gate by 2020. [DOE, 2012, p. 1-2]

Steam Methane Reforming (SMR) is the main H_2-production method. It involves the endothermic conversion of methane and high-temperature water steam into hydrogen and carbon monoxide (1) at temperatures of 700 to 850 °C and pressures of 0.3-2.5 MPa. The product gas contains approximately 12% CO, which can be further converted into CO_2 and H_2 through the water-gas shift reaction (2). Projections based on high-volume production indicate that reforming natural gas at the fuelling station can produce hydrogen at a cost close to 2 USD/kgH_2. SMR H_2-production costs are directly proportional to the natural gas price. SMR efficiencies are in the range of 65-85%. Reforming may also be used for the H_2-production **from bio-derived liquids**, such as ethanol and pyrolysis oil.

Reforming: C_nH_{2n+2} / $C_nH_{2n+2}O_n$ + n H_2O ↔ n CO + (2n+1) H_2 (1)

Water Gas Shift: CO + H_2O ↔ CO_2 + H_2 + heat (2)

Natural gas reforming is more efficient when carried out centrally in a large plant, where waste energy can be recovered to produce electricity.

Partial oxidation of natural gas with oxygen is an H_2-production process to yield carbon monoxide, hydrogen (3) and heat in an exothermic reaction. A more compact design of the facility is possible as there is no need for any external reactor heating. The CO produced is converted to H_2 as described in equation (2).

2 CH_4 + O_2 ↔ 2 CO + 4 H_2 + heat (3)

Hydrogen could be used as an energy storage system, cost-effective electrolysis is the missing link in the electricity-hydrogen conversion chain. The versatility of hydrogen storage solutions are not restricted to providing electricity back to the grid (in 2012 an estimated 128

GW of storage power capacity was installed world-wide – 99% of that was pumped hydro storage), but using in FCVs or combustion turbines. Hydrogen reacts in an exothermal reaction with oxygen to water, this is the basic reaction in any FC or - the other way round - water is split into hydrogen and oxygen in the **electrolysis**. The chemical bond of the hydrogen and oxygen in the water molecule is strong.

$$286 \text{ kJ/mol (liquid water) or } 341.98 \text{ kJ/mol (gaseous water)} + 2\ H_2O \rightarrow 2\ H_2\ (g) + O_2\ (g) \quad (4)$$

H_2-electrolysis from water is a well-established technology at both large and small scale. Large scale H_2-production results in better efficiency and costs. Electrolysis using EU-mix electricity shows higher GHG-emissions than H_2-production from NG. Hydrogen produced from renewable produced electricity shows very high efficiency and very low GHG-emissions, (see *Figure 4-32*). For the H_2-production through electrolysis about 4.5 kWh/Nm³H_2 (alkaline electrolysis) or 4.3-9.0 kWh/Nm³H_2 (PEM-electrolysis, currently) are needed (3.55 kWh/Nm³H_2 for the chemical reaction). [Hollemann et.al., 1985, p. 253; Wenske, no year, p. 173]

Figure 4-30: Chloralkali electrolysis in Hürth Knappsack [Exzellenz NRW, no year, p. 6]

Alkaline electrolysis cells with an aqueous Potassium hydroxide solution as an electrolyte have been a mature technology for decades. The efficiency is in the range of 70-80%. The operational temperature is about 80-90°C, a high purity of the products is achieved (>99.8% H_2). To be cost competitive, R&D is necessary to reduce electrolysis capital and operating costs, in particular electricity consumption. For example, 'stranded' biogas (where the plants are not connected to the natural gas network) could be used for onsite power generation or hydrogen production. In Prenzlau, Enertrag operates a hybrid power plant (230 MW wind energy, 20 MW biomass). It produces hydrogen from excess wind energy through alkaline electrolysis with an efficiency of 75-82%. A mixture of at least 30% biogas and, at most, 70% of hydrogen is used to produce electricity when the wind energy production is not high enough to satisfy the demand in two CHPs. The H_2-blending increases the burning quality of the biogas. The overall efficiency of the hybrid power plant (electricity, heat and fuel) is about 65%. It also supplies hydrogen to the CEP filling station at Berlin Heidestraße. [Enertrag, 2012]

PEMFC-, compared to alkaline **electrolysis**, is suitable for smaller systems due to its modular nature, has a good ability to respond to load changes and has a simple design which still offers large cost reduction potentials. PEMFCs can operate at higher current densities and are therefore more compact. Discontinuous operation should reduce the H_2-costs by enabling the arbitrage of grid electricity price variations and more importantly by generating revenues from adjusting electricity withdrawal upwards or downwards on demand. It is conceivable that operators of wind or solar farms can produce their own H_2-fuel since the respective electrolyser technology is already on offer. In a decentralised fuel production market the importance of self provision will increase; probably providing hydrogen at lower pressure levels to reduce costs.

Solid Oxide Electrolyser Cells are based on the SOFC operating at 700 to 1,000°C. At these temperatures, the electrode reactions are more reversible and less electricity is required to split water into hydrogen and oxygen. [DOE, no year (1), p. 26-30, IEA/HIA] The costs of H_2-production via electrolysis depend heavily on electricity prices. **Photovoltaic systems** coupled to electrolysers are commercially available. The systems offer some flexibility as the output can be electricity from photovoltaic cells or hydrogen from the electrolyser.

Gasification is a process in which coal or biomass is converted into gaseous components by applying heat under pressure and in the presence of air/oxygen and steam. A subsequent series of chemical reactions produces a synthesis gas, which is then reacted with steam to produce a gas stream with an increased H_2-concentration. In practice, high-temperatures are favoured to maximise carbon conversion to gas, thus avoiding the formation of significant amounts of char, tars and phenols. A typical reaction for the process is given in equation (5). The gas received can be separated and purified. With **CO_2-Capture and Storage** (CCS), hydrogen could be produced directly from coal with near-zero GHG-emission.

$C(s) + H_2O + heat \leftrightarrow CO + H_2$ (5) [DOE, no year (2), IEA/HIA]

However, there are currently, no concrete CCS projects close to realisation in Europe, except for offshore CO_2-rejection at gas fields in Norway. The Swedish energy company Vattenfall abandoned its plans for the erection of a CCS demonstration plant with an investment of 1.5 G€ in Jänschwalde, Brandenburg in 2011.[128] Even when a compromise was reached to allow testing and demonstration of CCS in Germany in June 2012, the situation did not change. [Deutscher Bundestag, KSpG, 17.08.2012]

Advanced production processes which are currently under research comprise **High-Temperature Thermochemical Water-Splitting** at about 3,000°C and **(Solar/Nuclear) Thermo-Chemical Cycles**. Furthermore, certain microbes, such as green algae and cyanobacteria, produce hydrogen photo-biologically by splitting water in the presence of sunlight. The US DOE homepage and the IEA Hydrogen Implementation Agreement provide a good overview on potentials and related cost targets. [DOE, no year (2), IEA/HIA]

Hydrogen is not a primary energy source but an energy vector making it a very complex fuel. A Well-to-Wheels (WtW) analysis is used to assess the impact of different fuel production pathways (Well-to-Tank (WtT)) and powertrain options (Tank-to-Wheel (TtW)) on energy consumption and GHG-emissions. EUCAR (European Council for Automotive R&D), CONCAWE[129] (Conservation of Clean Air and Water in Europe) and JRC (Joint Research Centre of the EU Commission) jointly elaborated a common methodology for WtW-analysis and are regularly up-dating the data-set of energy use and GHG-emissions for a wide range of fuel and powertrain options since 2003. Details on the methodology itself are available on the JRC homepage. Even if the results for some power trains are already outdated, it shows that Fuel Cell Hybrid Vehicles (FCHV) could be a very CO_2-efficient propulsion system, also when running on hydrogen produced from natural gas.

WtW analysis is absolutely essential for hydrogen where a large part of the energy usage and all of the GHG-emissions occur at the production stage. H_2-production can be envisaged either centrally in a large plant or locally in a small plant serving one or more refuelling sites. EUCAR evaluated the “on-site” option as plausible for natural gas reformers, wood gasifiers and electrolysers, (see *Figure 4-31* and *Figure 4-32*). Central plants are more efficient, but

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128 http://www.morgenpost.de/berlin/article1846890/CCS-gescheitert-Vattenfall-kippt-Klimaprojekt.html, 26.12.2011

129 The European Council for Automotive R&D (EUCAR) is an industrial association from the automotive industry for collaborative automotive and road transport R&D. [http://www.eucar.be/]. CONCAWE was established in 1963 by a small group of leading oil companies to carry out research on environmental issues relevant to the oil industry. Today, membership includes most oil companies operating in Europe. [http://www.concawe.be]

hydrogen needs to be transported to the customer, see section 4.2.4.3. Gasification processes tend to be less energy-efficient than natural gas reforming because of the nature of the feedstock.

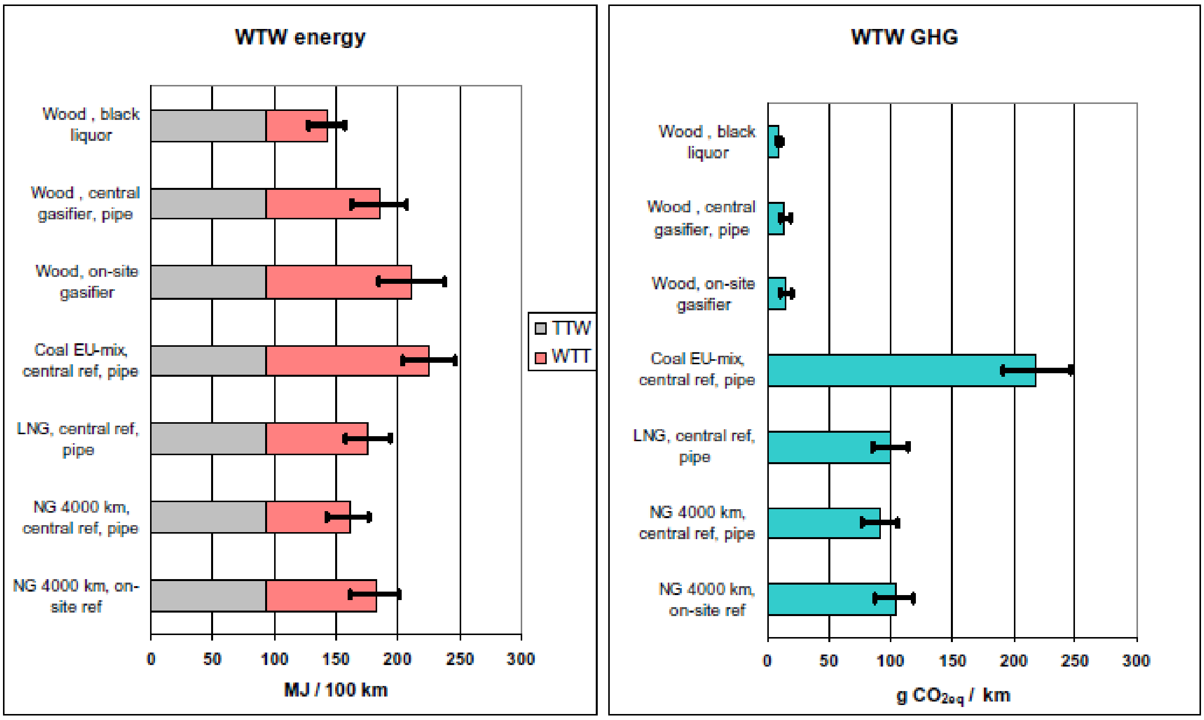

*Figure 4-31: WtW total energy requirement and GHG-emissions for **chemical transformation** CGH_2-pathways (2010+ non-hybrid FCVs)*

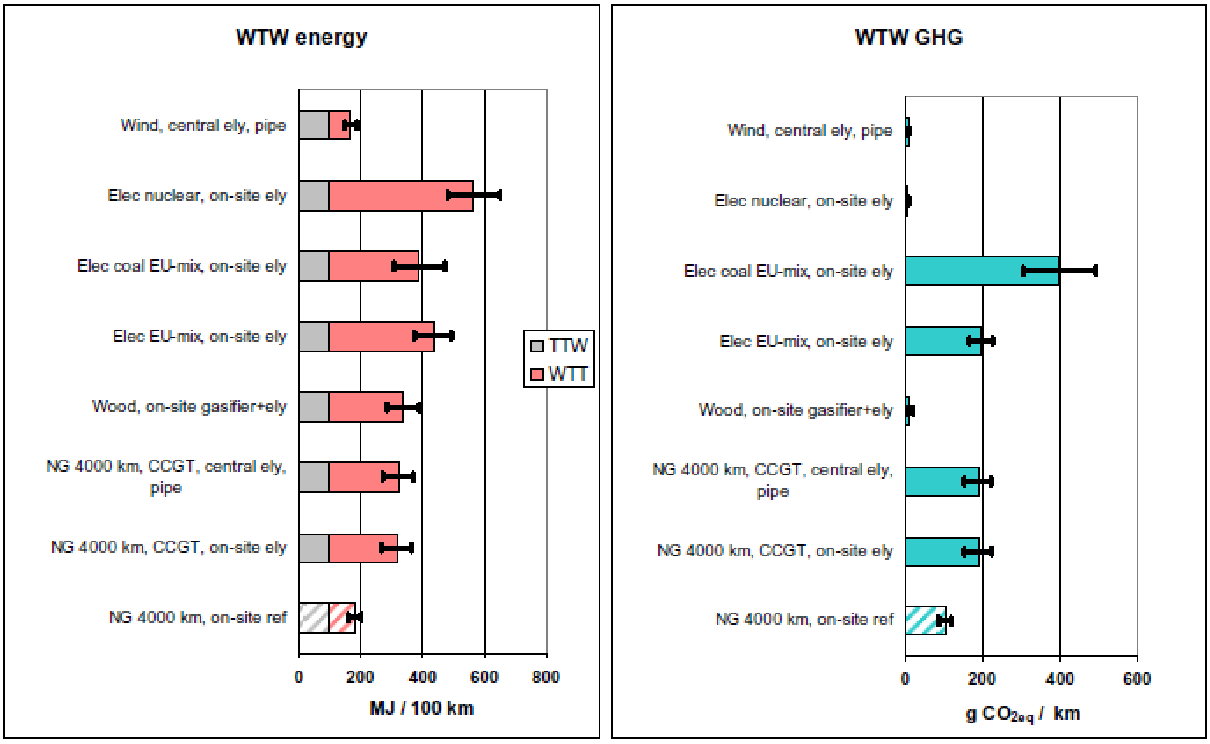

*Figure 4-32: WtW total energy requirement and GHG-emissions for CGH_2 via **electrolysis** (2010+ non hybrid FCVs) [Edwards et.al., 2011, p. 61, 62]*

The use of renewable energy sources for H_2-production is crucial to the market success of H_2FCV-technologies, because it provides benefits for a larger group of stakeholders and interests. The Forschungszentrum Jülich calculated a feasibility scenario for a 55% GHG-emission reduction (without the use of nuclear energy) in Germany by 2050. Hydrogen plays a crucial role in this scenario, see *Figure 4-33*. The scenario verified the feasibility of using H_2-storage to support the 'green' generation of 100% of the traded German electricity. This includes the provision of H_2-fuel to operate 75% of the German car fleet, i.e. M28 FCVs. This would need an H_2-production of 5.4 Mt/a, 84 GW H_2-electrolyser capacity installed, H_2-pipeline infrastructure of 12 k-km, k9.8 H_2-filling stations and H_2-storage capacity of 0.8-2.4 Mt to cover the seasonal or strategic 60-days-energy reserve.

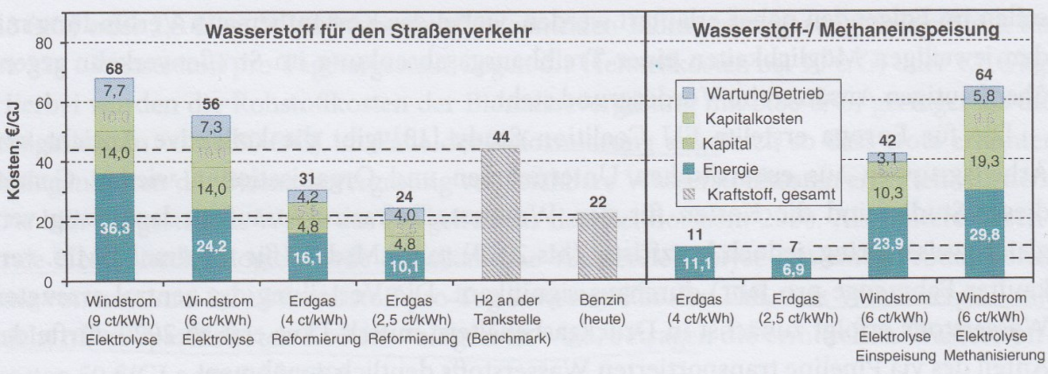

Figure 4-33: Cost-comparison of H_2-production and use alternatives [Grube et.al. 2013, p. 232]

The study showed that the GHG-reduction potential of hydrogen used in an FCV is 2.5-times higher than if hydrogen is used for H_2-reconversion to electricity. [Grube et.al. 2014, p. 17-18, 27][130] The scenario calculated an H_2-price of 56 €/GJ (6.72 €/kg) including all costs for transport and distribution compared to a petrol reference price of 22 €/GJ, i.e. 70 ct/l w/o taxes. The study also showed that the feed-in of hydrogen (42 €/GJ) to the natural gas grid is economically preferable to the feed-in of methane produced from hydrogen (64 €/GJ). However, both options are not competitive with the current natural gas price of 11 €/GJ (the study used a basis price of 6 ct/kWh electricity). [Grube et.al. 2013, p. 232]

However, further extension of renewable energies in Germany will require new storage solutions. Ludwig-Bölkow-Stiftung showed that up to 4 TWh excess wind energy could be produced only in Schleswig-Holstein by 2020 (20% of the overall onshore production). A study carried out within the NIP estimated a share of 10% of excess total wind energy in the North-Eastern region (including parts of Denmark). [Albrecht, 2010, p. 7; Stolzenburg, 2013, p. 6] However, H_2-production only from excess energy is not beneficial due to the low capacity use of the electrolyser.

In conclusion, the price of hydrogen heavily depends on the cost of the (primary) energy source, e.g. biomass, biogas, renewable electricity. The spatial mismatch between H_2-demand and production necessitates an infrastructure for a cost-effective H_2-transport. Hydrogen used as energy storage medium and fuel (energy consumer) may support the extension of renewable electricity generation.

Hydrogen may also be produced **onboard the vehicle through reforming**, but this technology pathway has not proved to be practical. Some car manufacturers[131] looked at

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130 Assumption: Energy demand FCV (1 kg/100 km) is 50% of ICE vehicle; WtT petrol/natural gas is 1.25, reconversion of H_2 or CH_4 has the same efficiency.

131 The main prototypes included: **Daimler**, NECAR 3 (A-class), 50 kW PEM, first methanol reforming FC, 1997; **Toyota**, RAV 4 FCEV, 25 kW PEM, methanol, 1997; **GM**, Zafira, 50 kW PEM, methanol, 1998; Honda, FCX-V2, 60 kW PEM, methanol, 1999; **Nissan**, R'nessa (SUV), 10 kW PEM, methanol, 1999; **VW**, EU Capri Project (VW Estate), 15 kW PEM, 1999; **Chrysler**, Jeep Commander 2 (SUV), 50 kW PEM, methanol, 2000; **Daimler**, NECAR 5 (A-class), 85 kW PEM, methanol, 2000; **Ford**, TH!NK FC5,

reforming petrol or methanol into hydrogen onboard the vehicles. Both processes worked, but added weight, complexity and cost to the vehicle. It is easier and more cost effective to produce the fuel at a central location. The first methanol reforming car was presented to the public by GM in 1997. The GM EV1 FCV was based on the all-electric EV1 automobile which was equipped with an FC range extender running on methanol. Daimler even announced marketing about M0.1 methanol reforming FCVs by 2004 in 1998. [WSS 1/98, p. 2] The methanol reforming options were dismissed as a fuel option for FC-drives by all vehicle manufacturers during the last decade. **Delphi** developed an SOFC-operated Auxiliary Power Unit to provide up to 9 kW_{el} for a wide range of transportation applications with onboard reforming of diesel or other fuels.[132]

4.2.4.3 Hydrogen transport and distribution

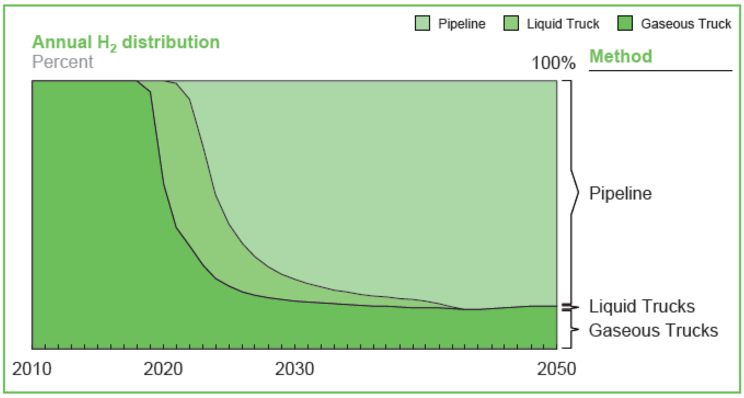

Figure 4-34: H_2-distribution scenario [McKinsey, 2010, p. 23]

Hydrogen is commonly transported as GH_2 in dedicated pipelines, as CGH_2 in pressurised cylinders or as LH_2 in cryogenic tanks (mostly on the road). Germany has a 240 km **H_2-pipeline** starting in Marl with end points in Castrop-Rauxel and Leverkusen as well as connection points in Krefeld und Oberhausen in North-Rhine-Westphalia. The pipeline is supplied by four H_2-production plants; six large industrial customers are supplied. The capacity of the pipeline is 0.04 Mm³/h at operational pressures up to 2.5 MPa. In addition, Linde is operating an H_2-pipeline to connect the production facilities in Leuna, Buna, Bitterfeld and Rodleben. Pipelines bear the advantages of reliability, an option of capacity balance between production plants and consumers, comparably low costs and high safety. [Air Liquide, 2009/2010, p. 4-11] The importance of pipeline transport is predicted to increase, if hydrogen were used as a vehicle fuel throughout Germany (see *Figure 4-34*).

Transport of bottles filled with CGH_2 or LH_2 is another transport option. Air Liquide operates the largest H_2-bottling centre in Europe in Marl. Hydrogen is produced through steam reforming, reaching qualities of up to 99.9999 Vol.-% and is compressed to 30 MPa.

Annually, k15H_2-bottles are filled with an operating pressure of 20 MPa. Furthermore, cartouches of two litre volume, i.e. composite bottles can be filled up to 70 MPa containing an energy content of 3 kWh. [Air Liquide, 2009/2010, p. 4-11] Transport of CGH_2 using tube trailers is only feasible for small volumes because the container mass is very high compared to the H_2-mass transported. An advanced truck may transport up to 6,845 m³ H_2 at 20 MPa, the empty weight of the truck is 39.4 Mg, the payload is 600 kgH_2, i.e. 20 MWh. For comparison, a road tanker has up to 28 Mg payload carrying about 32 m³ diesel or 36 m³ petrol, i.e. 320 MWh or 317 MWh respectively. Thus, up to 16 trucks are needed to deliver

85 kW PEM, methanol, 2000; **Daimler**, NECAR 5.2 (A-class), 85 kW PEM, methanol, 2001; **GM**, Chevy S-10 (pickup truck), 25 kW PEM, low sulphur, clean petrol, 2001; **Mazda**, Premacy FC-EV, 85 kW PEM, methanol, 2001; **Mitsubishi**, SpaceLiner Concept only, 40 kW PEM, methanol, 2001; **Toyota**, FCHV-5, (Kluger V/Highlander SUV), 90 kW PEM, low sulphur, clean petrol, 2001.

132 http://delphi.com/manufacturers/auto/fuelcells; 13.04.2015

the same amount of energy delivered by one petrol or diesel truck. A double-walled LH_2-trailer may transport 3.37 Mg H_2 on a 40-Mg-road train. [Westfalen, no year]

Figure 4-35: CGH_2-Transporter[133]

Hydrogen may also be stored and transported in the natural gas network, see section 4.1.1 for the results of the NaturalHy project. The DVGW (Deutscher Verein des Gas- und Wasserfaches e.V. - German Technical and Scientific Association for Gas and Water) suggested a possible mixture of 10-Vol%H_2 / 90-Vol%CH_4, but consequences on gas turbines, NGVs, household appliances, gas reservoirs etc. need to be investigated.[134]

Figure 4-36: LH_2-trailer & storage [Linde 2003, p. 4]

The EU25 natural gas network has a total length of1.8 Mkm (0.2 Mkm transportation network+ 1.6 Mkm distribution network) and includes 120 natural gas reservoirs. The total storage capacity of the German network comprises more than 200 TWh.[135] The DVGW and DIN set standards for the mixture of hydrogen to the natural gas network, respectively for use as vehicle fuel. **DIN 51624 'Automotive fuels –CNG – Requirements and test methods'** regulates the maximum H_2-content of CNG to 2%, the methane number (MN) is set to 70. In this way, a standard natural gas pipeline with a diameter of 200 mm and an operating pressure between 4-8 MPa may store about 33 kgH_2[136] per 100 km pipe-line. However, blending of hydrogen changes the methane number and therefore the anti-knock properties. The MN for pure methane is defined at 100, representing very good anti-knock properties, the MN of hydrogen is zero. A mixture of 10% H_2 to methane results to approx. MN80. Independent of the regulations of DIN 51624, the quality of natural gas for the public gas supply is regulated by **DVGW**

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133 own photograph

134 http://www.dvgw-innovation.de/fileadmin/dvgw/gas/netze/forschungsergebnisse_smartgrid.pdf/, 15.11.2015

135 http://www.fraunhofer.de/de/presse/presseinformationen/2010/04/strom-erdgas-speicher.html, 23.04.2013

136 273.3 K, 6 bar, ρ = 0.53034 kg/m³, 2 Vol.-% hydrogen

regulation 'G 260 – Gas properties'. The limiting factor for the addition of hydrogen to a natural gas of H-quality is the upper heating value of ca. 11.0 kWh/m³ (operating range of domestic installations), this would allow for a maximum addition of 5.7 Vol.-% H_2. DVGW regulation '**G262 – Use of gases from renewable sources in the public gas supply**' limits the H_2-content to 5%. [Müller-Syring, 2010, p. 10, 39, 41]

H_2-filling stations differ in design which is mainly based on H_2-production (central/decentral) and storage (CGH_2/LH_2) strategy. The H_2-refueling station shall enable safe, reliable, complete and fast refuelling of the FCV's storage system with CGH_2. During all filling phases and modes, the refuelling station shall be responsible for the overall safety of refuelling the vehicle. An H_2-station shall allow for refuelling with and without data communication. During a communication fill, the vehicle primarily supports the station in achieving a high State of Charge (SOC) by transmitting vehicle data (including internal gas temperature and pressure) to the station, but this vehicle data shall not be used for safety critical operations. SOC is defined (SAE J2061) as the ratio of the current filling density to the maximum filling density (40.22 kg H_2/m³ at 70 MPa, 15°C or at 87.5 MPa, 85°C). It is a function of the pressure and temperature in the fuel storage system. 35 MPa and 70 MPa dispenser types exist. A **35-MPa dispenser** provides a maximum filling pressure of 43.8 MPa at 85°C. It uses a nozzle in accordance with SAE J2600 (24.0 kgH_2/m³ at 35MPa, 15°C). H_2-pre-cooling is usually not needed for 35 MPa fills of 5 kgH_2 in less than five minutes, because the H_2-flow is comparably small (less than 20 gH_2/sec). [Zero Regio, 2006, p. 11, 15]

Total developed a dedicated design to integrate hydrogen into a modern multi-purpose filling station (CNG, LPG, CGH_2, AdBlue), which could be cost-efficiently multiplied. The standard concept shall support the market introduction of H_2-fuel by reducing planning and procurement costs, bundling of call for tenders, etc. It includes the following components:

Module 1: On-site H_2-storage and delivery of CGH_2: CGH_2 is delivered in trailers at a pressure of 20 MPa. Standard trailers transport 230 to 370 kgCGH_2, thus a small filling station used at full capacity would need a delivery every one to two days. The filling station has a connection point for pressure equalisation with the trailer. Alternatively, LH_2 is delivered or local H_2-production would fill the storage containers. The H_2-storage system includes pressure measuring instruments, a ventilation system and shut-off valves for inspection and maintenance works. An emergency valve installed close to the storage system allows the compressors to be isolated from the storage system.

Module 2: H_2-compression: There are two principal options for the pressure provision to fill vehicles: pressure could be built-up by compressors according to demand or pressure cascades are used. Pressure cascades combine the advantages of fast filling (if the cascades are fully filled) and a lower compressor / electricity grid peak power need, i.e. a power input of less than 100 kVA is necessary. The compressor can be operated at constant power resulting in lower component wear and lower operating costs. The H_2-storage capacity needs to be adapted to the compression system, e.g. 3-6 sets à 68 bottles at 20 MPa as input storage. Hydrogen is compressed in a cascade of two or three pressure steps, e.g. using a 50 MPa compressor for a first pressure level of 45 MPa and a 100 MPa compressor for the second pressure level of 90 MPa (using high-pressure H_2-storage tanks at 85 MPa). An H_2-compression system includes the compressors, a cooling system, process and engineering controls and safety devices. Safety devices shall control the pressure and temperature to ensure a high or low pressure alarm, avoid oxygen injections to the H_2-system and support the avoidance of the transmission of vibrations from the compressors to the piping system.

Today, filling stations offer CGH_2 at 35 MPa and 70 MPa, but 35 MPa filling technology for cars will be phased out during the next years. H_2-compression often uses ionic compressors, i.e. an H_2-compressor based on a ionic liquid piston instead of a metal piston. This ionic liquid of organic salts is nearly incompressible, the solubility of hydrogen in the ionic liquid is very low. The organic salts remain liquid within a specified temperature range. Because they do not have a vapour pressure, they do not evaporate or mix with the hydrogen, i.e. no contamination of hydrogen occurs. The hydrogen is compressed in the cylinder by the up-and-down motion of the liquid column, similar to the reciprocating motion of an ordinary piston. The ionic liquid has a good thermal capacity, discharging the compression heat to the atmosphere. Ionic compressors are considerably more efficient than conventional compressors, because the isothermal compression needs least compression energy.[137] Compression energy demand also depends on the initial pressure level; the theoretically energy demand for isothermal compression is from:

- 0.1 to 90 MPa: 2.44 kWh/kgH_2 (at 293 K, 0.101 MPa ambient conditions), i.e. 7.5% of the lower heating value of hydrogen (H_{2u}) [Klell, 2010, p. 10],
- 0.1 to 2 MPa: 1.02 kWh/kgH_2 (at 300 K, 0.101 MPa ambient conditions),
- 2 MPa to 35 MPa 1.05 kWh/kgH_2 (at 300 K, 0.101 MPa ambient conditions),
- 2 MPa to 70 MPa 1.36 kWh/kgH_2 (at 300 K, 0.101 MPa ambient conditions)-

In practice, more energy is needed to fill vehicles due to compressor inefficiencies and heating up of the gas during fast fills. A reciprocating compressor with a capacity of 1 MgH_2/day can achieve an isentropic efficiency of about 56% and a motor efficiency of 92%. Project data from on-site 70 MPa H_2-compression is 1.7 to 6.4 kWh/kgH_2. Additional energy (0.15 kWh/kgH_2) is required for pre-cooling to -40°C to limit the inner tank temperature during fast filling to 85°C or lower. [DOE, 2009 (2)]

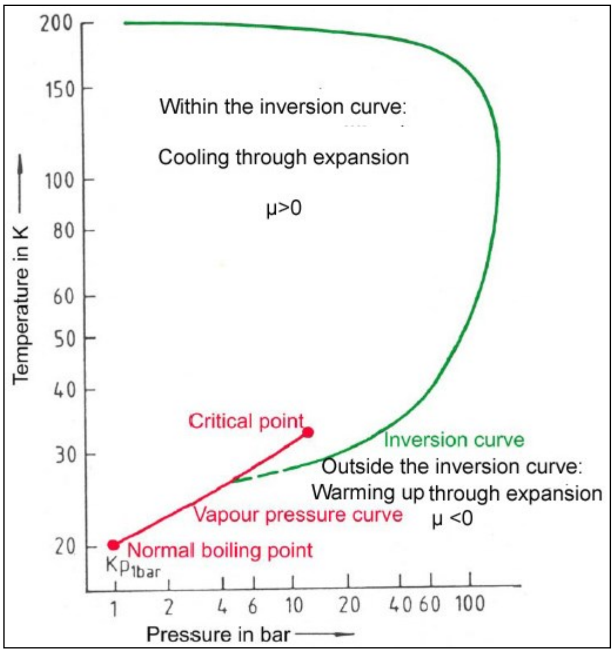

Figure 4-37: H_2-Thompson inversion curve [Neumann, 2007, p. 37]

The p, V, T-behaviour of real gases strongly depends on the attraction and repulsion forces of the particles. Due to the negative **"Joule-Thomson-coefficient"** of hydrogen in a wide temperature range, the H_2-temperature increases during the filling process when pressure is released and enthalpy (energy content of the system) is kept constantly (see *Figure 4-37*). The Joule-Thompson effect is caused by the interaction of the gaseous particles. If particles attract each other, work has to be done to increase the distance of two particles. This energy is taken from the kinetic energy of the particles, i.e. the gas cools down. If the particles repel each other, the energy stored under compressed conditions is higher than in an expanded gas, thus during expansion energy is released, the particles move away from each other, are more free to move, the kinetic energy increases and, with this, the temperature of the gas. Repelling or attraction of particles depends on the gas temperature.

137 http://www.lindeus.com/en/innovations/hydrogen_energy/fuelling_technologies/ionic_compressor.html, 26.12.2012

Real gases change behaviour at their inversion temperature, the inversion temperature of air is 450°C, that of hydrogen -80°C (0.101 MPa). [HSL, 2008, p. 2-4]

For the pressure equalisation to about 10 MPa between the first pressure cascade level and the vehicle tank a temperature increase of 20 K has to be expected, depending on cascade and tank volume as well as on their initial pressure levels. During a complete fast fill the temperature increases by about 40 K, reducing the hydrogen mass stored by 5-15%. The temperature equalisation with the ambient environment needs one to two hours. [Klell et.al. 2007] Filling tests at a 2x 5 kg 35 MPa system filled with a mass flow of 33 gH_2/sec showed a temperature rise from 25°C to 60°C during filling to 34.8 MPa. [own project data]

Module 3: CGH_2-dispenser: H_2-tank couplings exist for 35-MPA bus and LDV (TK15-coupling) and 70-MPa-car filling (TK17-coupling) according to SAE J2600 and SAE J2799. The 70-MPa-compression system is equipped with **H_2-cooling (-40°C)** to allow fast-filling of 5 kgH_2 within three minutes. The vehicle and the dispenser communicate via an infrared interface. Pre-cooled hydrogen (5°C) is further cooled-down to -40°C directly at the dispenser to avoid losses in the piping. The refuelling station shall be capable of setting the nozzle outlet/vehicle inlet temperature of the pre-cooled H_2-gas as a function of the ambient temperature (in accordance with SAE J2601 for A-70 filling stations). The temperature of the pre-cooled hydrogen at the nozzle outlet shall never be lower than -40°C (due to materials restrictions in the vehicle's fuel system). The fuel hose needs to comply with the normal stress at a public filling station concerning pull, torsion, wear and kinks. Each fuelling point includes an H_2-mass flow device, a sales display and a card reader for customer-friendly invoicing. The basic requirements for a successful market introduction (shown by NG introduction) is refuelling by means of multi-dispensers and self-service.

The filling station shall also ensure that the Joule Thomson effect occurs on the station side (ideally upstream of the pre-cooler, which shall be installed downstream of the smallest flow restriction in the complete refuelling path), in order to prevent the tanks from overheating and also to allow for complete fills (without slowing down the refuelling process). The fuelling station shall determine the fuelling process when the fuel system pressure reaches the calculated target pressure (max. 87.5 MPa (70-MPa-dispenser) or 43.8 MPa (35-MPa-dispenser)) or target capacity. A dedicated, highly reliable, calibrated and hardwired station-side pressure sensor signal shall be used for this purpose. Final, a fully mechanical protection level shall prevent of any further pressure increase in the fuel system by activation of a station-side PRV (set at 96.25 MPa for a 70-MPa dispenser and 48.13 MPa for a 35-MPa dispenser). At this pressure, the refuelling station shall release the pressure via a vent line. [Zero Regio, 2006, p. 7-12] A verifiable flow meter for hydrogen is still under development. However, filling stations are currently issuing invoices based on non-verified measurements, the risk of measurement uncertainty remains with the filling station operator. However, it is expected that a device will be available for extension of the German filling station network by 2015. [own project data]

Module 4: The various modules are connected by **pipings, armatures and connections** designed according to the high demands in terms of pressure, temperature and contact with hydrogen. All welding jobs need to prevent H_2-embrittlement and cracking. The H_2-pipes to the H_2-dispenser are laid underground to protect them from collisions. The "H_2-Mobility-Initiative" developed standard design concepts for H_2-refuelling stations (see *Figure 4-38*).

Cars and LDVs are filled according to the standard "*SAE J2601 Fuelling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles*". The maximum content of a vehicle tank is assumed to be 7 kg H_2 with an average filling of about 5.6 kg H_2. The availability of the filling station should be better than >95% referring to the opening time. In any case, assuming opening hours of 24/7, this would mean a breakdown of more than eight hours per week. Today, these breakdown times have not been reached; one reason is the poor capacity use of the stations as some of the equipment is designed for continuous operation, e.g. the refrigeration machine. The first operational experience from the CEP clearly shows that the refuelling process is not that easy to handle and still needs a lot of adaptation on both sides, the vehicle and the filling station. [own project data]

	Small HRS	Medium HRS	Large HRS
Number of refuelling positions	1	2	4
Number of fills per hour per position	6	6	10
Number of back to back fills per refuelling position per hour	2	2	10
Maximum waiting time to fuel consecutive cars [minutes]	5	5	n.a.
Minimum period to meet the requirements [hours]	3	3	24/7
Average number of fills per day	30	60	125
Maximum number of fills per day	38	75	180
Maximum hourly hydrogen throughput in kg	33.6	67.2	224
Average hydrogen throughput per day in kg	168	336	700
Maximum hydrogen throughput per day in kg	212	420	1,000
Number of cars served (approx.) per day	400	800	1,600

Figure 4-38: Performance characteristics of various H_2-filling station size classes [CEP project document]

4.2.4.4 Hydrogen on-board storage technology

ISO 15869:2009 defines the requirements on pressurised tanks (see section 3.4). Cryogenic CH_2-, metal hydrides, high-surface-area adsorbents and chemical H_2-storage are under research. *Figure 4-39* compares 2010 tank technology with future targets as set by DOE.

Performance and Cost Metric	Units	35 MPa	70 MPa	2010 Targets	2015 Targets	Ultimate Targets	Quantum 013[138]
System gravimetric Capacity	wt%	5.5	5.2	4.5	5.5	7.5	5.4
System volumetric capacity[139]	gH_2/l	17.6	26.3	28	40	70	39
Storage system cost	$/kWh	15.4	18.7	4	2	t.b.d.	
Fuel cost	$/l	1.11	1.14	0.5 – 0.8	0.5 – 0.8	0.5 – 0.8	
WtT-Efficiency (Hi)	%	56.5	54.2	60	60	60	

Figure 4-39: Assessment for CGH_2-storage systems and DOE-targets [DOE, 2009 (1)]

State-of-the-art FCVs use Type 4 fully wrapped composite fuel tanks (70 MPa) with no metal liner to achieve the required vehicle range. This inner-liner consists of a high-molecular-weight polymer that serves as an H_2-gas permeation barrier. The permeation of hydrogen from the storage tanks is negligible, the systems are classified as being tight during operation. [BGI 5108, 2009, p. 18] A carbon fibre-epoxy resin composite shell is placed over

[138] High Pressure Lightweight Type IV H_2Cylinders-129L [http://www.industrycortex.com/datasheets/-profile/1503495614/129l-hydrogen-tank-fuel-systems-division-high-pressure-lightweight-type-iv-h2-cylinders-129l-advanced-components-for, 15.11.2015]

[139] Stored mass of hydrogen per litre of storage system.

the liner and constitutes the gas pressure load-bearing component of the tank. Finally, an outer shell is placed on the tank for impact and damage resistance. The pressure regulator for the 70 MPa tank is located in the interior of the tank. There is also an in-tank gas temperature sensor to monitor the tank temperature during the filling process. The minimum allowable tank working pressure is 0.3-2.0 MPa, corresponding to a minimum SOC of < 3% (at 1.0-2.0 MPa, 15°C; depending on tank and OEM), the minimum and maximum expected ambient temperature range is -40°C to +50°C and the maximum allowable fuelling flow rate is 60 gH_2/s. The vehicle's fuel system may include a flow restriction (orifice) in its filling line intended to limit the inlet gas flow rate to 60 to 65 g H_2/s.[140] The 70 MPa-tank system of the 2015 FCV generation is expected to cost about 11-13 k€. [Bernhardt et.al., 2014, p. 5] The cost of high-pressure CGH_2-tanks is essentially influenced by the cost of the carbon fibre that is used for lightweight structural reinforcement. Carbon fibres have to meet the required high-pressure and safety specifications. Cost, weight, volume, refuelling times, compression energy penalties and heat-management requirements are main development targets.[141]

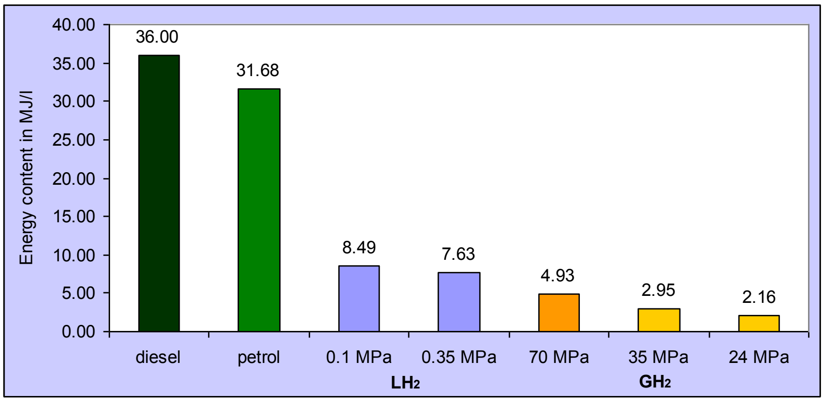

Figure 4-40: Storage density of various fuels [Wolf, 2003, p. 10]

In particular, CGH_2-storage is disadvantaged by a lower energy density compared to other fuels, (see *Figure 4-40*). One kg H_2 stored at 70 MPa needs a storage volume of 25 l. The Mercedes B-Class carries a tank of 4 kgH_2 to provide a range of > 400 km. Two approaches are being pursued to increase CGH_2-storage capacities. H_2-storage in cryo-compressed tanks at fixed pressure and volume could increases gas gravimetric capacity by a factor of four as the tank temperature decreases from room to liquid nitrogen temperature (77°K). However, system volumetric capacity increases less than this due to the increased volume required for the cooling system. Conformable tanks could take maximum advantage of available vehicle space. Concepts for conformable H_2-tanks are based on structural supporting walls or internal cellular-type load bearing structures and include comb structured bundles of bottles, improved weld seams and isotensoid[142] winding with an improved volumetric density. [DOE, no year (3)]

The mass of CGH_2 stored is calculated using the density of the fuel, which strongly depends on the compression factor Z for real gases:

$Z = \frac{p \cdot v}{R_s \cdot T}$, v = $\frac{V}{m}$; Rs= $\frac{R}{M}$	Rs = 4,124 [J $mol^{-1}K^{-1}$], specific gas constant R = Universal gas constant [J $mol^{-1}K^{-1}$], M = Molar mass [kg mol^{-1}]
$\mapsto m_{fuel} = \frac{p \cdot V}{R_s \cdot T \cdot Z}$	Z = Compression factor; v = Specific volume [m^3 mol^{-1}] p = Pressure [N m^{-2}]; T = Temperature [K]; V = Volume [l]

The H_2-compression factor is linearly dependent on the pressure under isothermic conditions. The axis intercept b is constant with the value of one. In addition, the slope of the

140 http://www1.eere.energy.gov/hydrogenandfuelcells/storage/hydrogen_storage.html, 23.04.2013
141 http://www1.eere.energy.gov/hydrogenandfuelcells/storage/hydrogen_storage.html, 23.04.2013
142 A contour in a filament-wound reinforced plastic pressure vessel; the filaments are placed on geodesic paths so that the filaments exhibits uniform tension throughout their length under pressure loading.

compression factor z also dependents linearly on the temperature in a range of 260 to 310 K. In practice, this relationship could be used to calculate an approximate fuel consumption for various p,T-conditions from the pressure reading results, (see *Figure 4-41*).

The **use of LH_2** in vehicles is double-edged. LH_2 offers a higher volumetric density (0.07 kg/litre) than GH_2 at 70 MPa (0.03 kg/litre), but requires H_2-liquefaction,which has an unfavourable WtW energy chain efficiency. Cryogenic storage of LH_2 at -253°C in a vehicle has several critical practical issues: The H_2-boil-off causes costs, reduces the vehicle efficiency as well as range and raises safety considerations for vehicles parked in confined spaces, see BGI 5108. Insulation is needed to keep the temperature ultra-low to reduce the boil-off. Insulation lowers the gravimetric and volumetric storage capacity. Latest used cryogenic vessels for passenger cars consisted of double-wall cylindrical tanks with an H_2-storage mass of up to 10 kg. The preferred material for the tanks consists of at least 2 mm stainless steel, since it is very resistant to H_2-brittleness and it shows negligible H_2-permeation. The weight of the whole tank system including valves and heat exchanger is more than 100 kg. [Krainz et.al., 2004, p. 1]

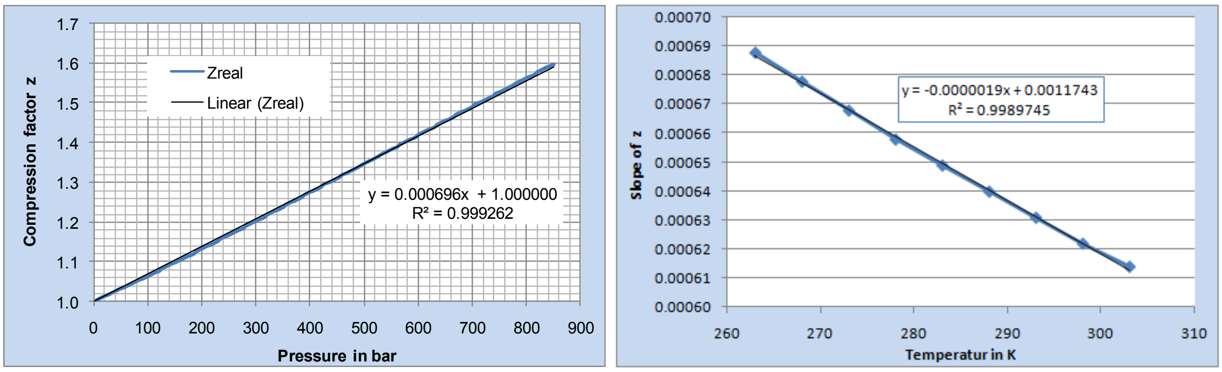

Figure 4-41: P/Z-diagram of molecular hydrogen, Z_{350bar} = 1.236, $Z_{70\,MPa}$ = 1.489, T = 273.15 K and slope of z for various temperatures, V= 202 litres [143]

The minimum theoretical energy to liquefy hydrogen from ambient (300 K, 0.101 MPa) conditions is 3.3 kWh/kg LH_2 or 3.9 kWh/kg LH_2 with conversion to para-LH_2 (LH_2 has two isomers, 99.79% consist of para-LH_2). Actual liquefaction energy requirements are substantially higher, typically 10-13 kWh/kg LH_2 (i.e. 30% of H_{2u}), depending on the size of the liquefaction operation. Novel liquefaction methods such as active magnetic regenerative liquefier may require as little as 7 kWh/kg LH_2. [DOE, 2009 (2)] The use of LH_2 was tested[144] by most of the manufacturers developing H_2FCVs, but has been completely abandoned by all manufacturers by now. All newly constructed H_2-filling stations do not provide LH_2.

143 Own calculation using *http://webbook.nist.gov* database

144 **Renault**, Laguna wagon, 30 kW PEM, 1997; **Daimler**, NECAR4, A-Class, 70 kW PEM, 1999; **VW**, HyMotion, 75 kW PEM, 1999; **BMW**, Series 7 (745 h), Sedan, petrol ICE, 5 kW PEM fuel cell APU, 2000; **BMW**, Hydrogen7, LH_2/petrol dual fuel ICE, 2000, **GM/Opel**, HydroGen1, Zafira van, 80 kW PEM, 2001; **GM/Opel**, HydroGen3, Zafira van, 94 kW PEM, 2001.

4.2.4.5 Use of hydrogen as vehicle fuel

Figure 4-42: First H2ICE vehicle [Connor, 2011, p. 4]

In 1807 François Issac de Rivas built the first hydrogen internal combustion engine, and although the design was quite simple (see *Figure 4-42*), it was a more than 50 years ahead of the development of the first petrol internal combustion engine by Jean Lenoir in 1863. Several car-makers developed H_2ICE engines[145] in the past but development has stopped. The main reason is the low energy efficiency compared to FCVs or diesel HEVs. The high H_2-consumption results in high fuel costs, low range or / and the need for a large H_2-storage or the use of LH_2. After termination of H_2ICE-technology development, **the future use of hydrogen in the transport sector is closely interlinked with the development of FCV-technology**. The German scientist Christian Friedrich Schonbein was the first to publish the principle of FC-operation, where oxygen and hydrogen are used as the anode and cathode reactants in 1838. Sir William Grove demonstrated the first FC in 1839 and published in the Philosophical Magazine and Journal of Science. *Figure 4-43* shows the first electrochemical apparatus demonstrating the FC-concept. After this phase of early research, FC-technology development was laid down until the 1950s, (see section 6.2.2.1). Today, FC-technology has manifold areas of application, see *Figure 4-44*. [DOE, 2009 (2)]

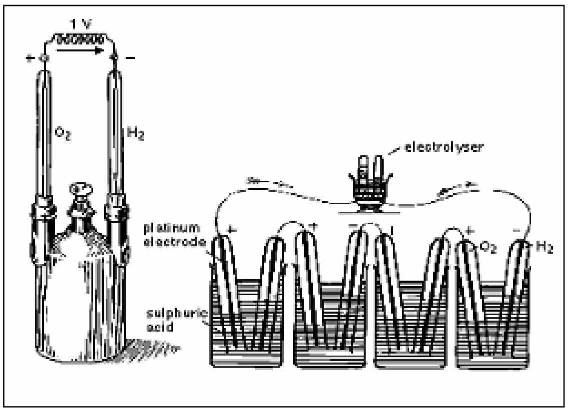

Figure 4-43: First FC-apparatus, 1842 [Baker et.al., 2011]

Several types of FCs exist, they are distinguished by their various types of electrolytes. **Polymer Electrolyte Membrane**[146] **FCs** (PEMFC) are applied in portable devices, domestic cogeneration appliances and in FCVs. The most significant advancements in PEMFC components, stacks and applications occurred from 1980 to 2000 led by Ballard Power Systems. Major breakthroughs included improvements in electrodes, micro-porous layers, catalysts and catalyst layers, membrane electrode assemblies, flow fields and low volume manufacturing. Early PEMFCs used platinum black (a fine, black powder of platinum with good catalytic properties) at very high loadings, increasing costs. Moving to carbon supported catalysts and new Membrane Electrolyte Assemblies (MEAs) resulted in a decrease in platinum loading and increased performance allowing to consider commercial automotive applications for the first time (by the end of the 1990s). Today, PEMFC technology is widely regarded as the most promising technology for LDV transport application. PEMFCs offer a compact system with high power density.

The components of an PEMFCV-system are summarised in *Figure 4-45*. The **FC-system** and its ancillary components regulate the operating conditions so that sufficient hydrogen

145 **BMW** Hydrogen 7, bivalent petrol/LH_2, 2000; **BMW** mini Cooper, LH_2, **Ford** P2000, CH_2, 2000; **Mazda** RX 8 RE, CH_2, 2004; **Mitsubishi** Nessie, 2005

146 A membrane is a layer of material which serves as a selective barrier between two phases. It remains impermeable to specific substances when exposed to a driving force such as a concentration gradient. Other components are allowed to passage by the membrane into the permeable stream.

and oxygen are made available for the FC at the appropriate pressure in accordance with the actual driving condition. It also dispenses surplus heat via the coolant circuit and removes water vapour and nitrogen from the vehicle. Almost all FCVs produced to date include an energy storage (mostly Li-ion batteries) that supports the dynamics of the entire drive system, provides additional energy for peak load operation and improves the overall efficiency by recuperating braking energy. Approximately only 30% of the diesel engine power that would otherwise be required has to be installed.[147]

Application Type	Portable	Stationary	Transport
Definition	Built into or charge up products designed to be moved, including APUs	Provide electricity &heat, not designed to be moved	Provide propulsive power or range extension to vehicles
Typical power range	5 W to 20 kW	0.5 kW to 400 kW	1 kW to 100 kW
Typical technology	PEMFC, DMFC (Direct Methanol FC)	MCFC, PAFC, PEMFC, SOFC[148]	PEMFC, DMFC
Examples	- Non-motive APU (camper vans, boats, lighting) - Military apps (portable soldier-borne power, skid-mounted generators) - Portable products (torches, battery chargers, personal electronics, cameras, laptops, education kits, toys)	- Large, small and micro stationary CHPs - Uninterruptible power supplies (UPS)	- Materials handling vehicles - FCVs - Trucks and buses

Figure 4-44: Types of FCs and applications [FuelCell today, 2011, p. 4]

In addition, though the FC is able to work dynamically, this operation mode reduces the FC life-time. The FCV itself is propelled by one or more electric motors. Its salient characteristics (high efficiency and full torque even at very low engine speeds) determine the FCV's driving dynamics and overall FCV-efficiency.[149]

An H_2-PEMFC operates on two coupled half reactions: the Hydrogen Oxidation Reaction (HOR) at the anode and the Oxygen Reduction Reaction at the cathode (ORR). The ORR is a complex process. Due to the acid environment, the low operating temperature of a PEMFC and slow reaction kinetics a precious metal bearing catalyst is necessary. The anode and cathode electrochemical reactions are:

Fuel cell system including:
Fuel cell stacks
Air and fuel loop
Humdifier and water recovery loop
High and low temperature coolant loop
Sensors
On-board CGH_2-storage, see section 4.2.4.4
Vehicle electrical system components
(Hybrid) drive train, see section 4.2.3
Traction inverter modul to control the traction motor
Vehicle frame, body, interior or comfort related features

Figure 4-45: Components of an FCV

Oxidation: $2\,H_2 \leftrightarrow 4\,H^+ + 4\,e^-$ $\quad E_a^0 = 0.00$ V versus SHE[150]

Reduction: $O_2 + 4\,H^+ + 4\,e^- \leftrightarrow 2\,H_2O$ $\quad E_c^0 = 1.229$ V versus SHE

Overall net reaction: $2\,H_2 + O_2 \leftrightarrow H_2O + \text{heat}$ $\quad E° = 1.23$ V [Kurzweil, 2013, p. 2-4]

147 http://www.proton-motor.de/hybridsystems.html?&L=0, 23.01.2013
148 MCFC: MoltenCarbonate FC; PAFC: Phosphoric Acid FC; SOFC: Solid Oxide FC
149 http://www.daimler.com/dccom/0-5-1228971-1-1231030-1-0-0-1401206-0-0-135-0-0-0-0-0-0-0-0.html, 23.04.2013
150 Standard hydrogen electrode

However, at usual current densities such as 1 A/cm², a typical cell voltage is 0.7 V. The over-potential loss (60% of PEMFC's overall efficiency loss) is due to the slow ORR electrode kinetic. Work is $W = \Delta G = \Delta H - T\Delta S$ = (-286 kJ/mol) – (-49 kJ/mol) = -237 kJ/mol. Single cells are combined to stacks of typically 1-100 kW. [Jörissen et.al., 2013, p. 242]

An **FC is a flow reactor.** It directly converts the chemical energy of a fuel to electricity, its capacity is only limited through the stock of reactants. H_2-gas flows through channels of the anode (bipolar) plate, where the H_2-molecules dissociatively adsorb and are oxidised to protons (H^+) on the surface of a (platinum-based) catalyst. The PEM is a proton conductive membrane with acid side groups to conduct protons from the anode to cathode. The PEM is used as the electrolyte and separates at the same time the anode from the cathode in the electrochemical cell. The solid electrolyte reduces corrosion and less electrolyte management problems occur. PEMFCs are operated at temperatures of 80-100°C. New membrane developments target at operation temperatures of up to 120°C. [Jörissen et.al., 2013, p. 244] The low operation temperature allows for a quick start-up of the FC, but there are not many useful applications for the low temperature waste heat.

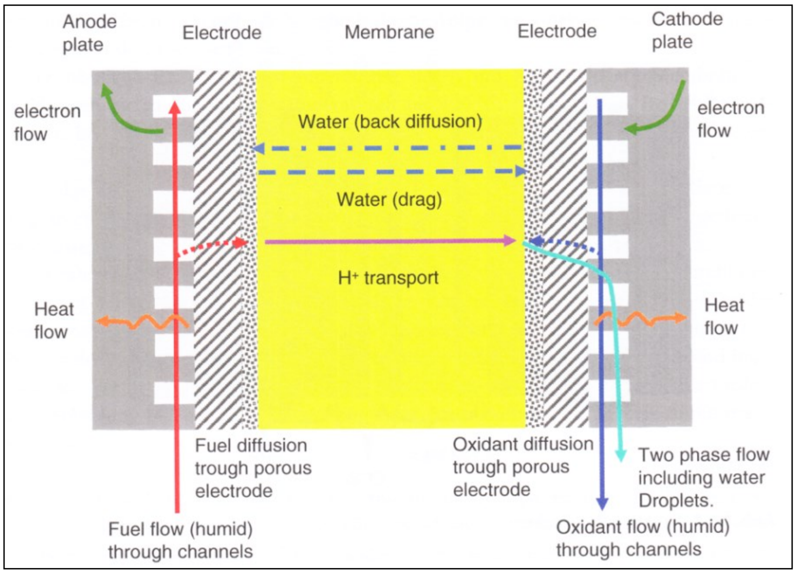

Figure 4-46: Hydrogen-oxygen PEMFC [Jörissen et.al., 2013, p. 244]

Protons diffuse through the PEM under an electrochemical gradient to the cathode plate. A stream of electrons follows an external circuit to the cathode generating a flow of electricity that can be used to power an electrical engine. Air flows through channels of the cathode. Oxygen molecules adsorb at the cathode, are reduced (electron acceptance) and react with the protons to water, again using a catalyst metal. From one kilogram hydrogen and eight kilograms oxygen nine kilograms of water are formed. At the cathode the partial pressure of water vapour and nitrogen increases as the oxygen of the air reacts to water. Nitrogen can pass the membrane driven by the partial pressure gradient and form a blanket on the anode. The accumulation of inert nitrogen and liquid water at the anode causes a voltage drop, which is recoverable by purging the anode through opening a downstream solenoid valve which creates a brief, high velocity hydrogen flow-through the anode. After the purge, the catalyst area contributing to the reaction increases and, hence, the measured voltage increases, but fuel (hydrogen) is also normally released.

Sufficient ventilation and other safety measures (e.g. sensors stopping the purging process when necessary) need to be installed to keep the hydrogen/air/mixture well below the explosion point. [Chen, 2012, p. 1-2] In order to enable cost reduction in the FC support systems a large reduction in the Nitrogen crossover is needed. Unless a change in the basic polymer of the PEM is used to achieve this, thinner membranes may not be practical. The amount of gas that needs to be pumped back in the purge circuit to eliminate the accumulated Nitrogen is proportional to the Nitrogen crossover rate. It inevitably wastes hydrogen and energy as well as requiring extra cells to produce this power.

The **membrane** is the main component of any FC as its characteristics term the demands to all other components and operation conditions. The proton conductivity of the electrolyte defines the FC's efficiency and power output. The proton flow against membrane resistance is a major source of performance loss. Minimisation of proton resistance is accomplished by using thin (approximately 15-180 µm) membranes. The electrolyte is sandwiched between two electrodes (bipolar plates). [Jörissen et.al., 2013, p. 243, 247] The desired properties for a membrane to be used as a proton conductor in an FC are:

- Mechanical strength as well as chemical, electrochemical, thermal and hydrolytic stability under FC operating conditions, i.e. the membrane needs to be resistant against the anode's reducing environment as well as the harsh oxidative environment at the cathode,
- Elevated proton conductivity to support high currents with minimal resistive losses and zero electronic conductivity, but extreme low permeability to electrons and reactant species to maximise efficiency,
- Good water uptakes at high temperatures of 80-100°C and chemical properties compatible with the bonding requirements of the Membrane Electrode Assembly (MEA), facilitation of rapid electrode kinetics, see below,
- High durability and production cost compatible with the FC commercial requirements. The MEA of the PEMFC makes about 75% of the overall PEMFC costs. [Zaidi, 2009, p. 8]

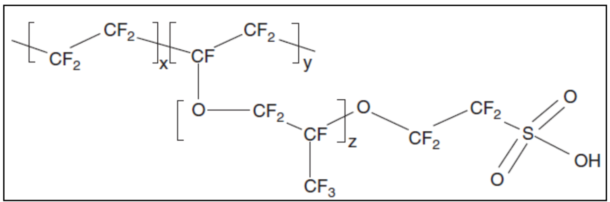

Figure 4-47: Chemical structure of PFSA Nafion membrane[151]

Advances made in FC-performance are closely associated with advances in polymer electrolyte technology. Until now, perfluorinated ionomer membranes have been used in commercial FC systems. Perfluorosulphonic Acid (PFSA, DuPont's trade name: **Nafion®**) is most commonly used. It consists of three regions: a hydrophobic polytetrafluoroethylene working like a stable backbone and providing the structural stability in reducing and oxidising environments. The side chains of -O-CF_2-CF-O-CF_2-CF_2- connect the molecular backbone to the hydrophilic PFSA which form sulphonic acid ion clusters. The highly electronegative fluorine atom is bonded to the same carbon atom as the -SO_3H group; this makes the sulphonic acid a superacid and makes PFSA highly conductive. The size of the pores and the structure depend on the number of side chains and the water content. [Jörissen et.al., 2013, p. 248-249] A well-humidified PFSA membrane can reach a conductivity of 0.2 S/cm at PEMFC operating temperatures. However, Nafion membranes degrade at high temperatures and conductivity is reduced. Safety concerns rise from the evolution of toxic PFSA intermediates and corrosive gases liberated at elevated temperatures above 150°C. Degradation of products could be a concern during the manufacturing or recycling process or vehicle accidents. [Zaidi, 2009, p. 5, 10] PFSA membranes are quite mature and it is becoming apparent that further improvements will be limited. They are expected to be viable in future FCV-generations when the cost of producing them is reduced significantly.

Water management in the FC is critical for PEMFC-operation and -efficiency, in particular, back diffusion of process water as well as flow resistance and flow distribution. Sufficient water must be absorbed into the membrane to ionise the acid groups; but excess water can condensate at the cathode and wet it, hindering gas diffusion and so diminishing FC-performance limiting the power output. The product water evaporates into the gas streams at the anode and cathode leaving the FC. [Viswanathan, 2007, p. 50-66] A great deal of effort was

151 http://www.polymersolutions.com/blog/wp-content/uploads/2011/06/Nafion_structure-300x114.png, 08.03.2014

made to reduce the resistance of membranes at low relative humidity (<20%). However, this increased the basic cost of the materials. Fundamental studies showed that zero relative humidity conduction cannot occur for sulphonic acid based membranes. [AFCC, 2015, p. 17]

PEMFC-technology requires environmental air/reactant gas **humidification** to maintain the performance and life of the FC electrolyte membrane. State-of-the-art technologies for PEMFC-humidification are mainly related to the direct injection of water into the gas stream or to the humidification of a gas stream by flowing of the air along a wetted membrane. External humidification utilises 'gas-to-gas' membrane humidifiers to humidify FC reactant gases. This allows heat and moisture from the FC-exhaust to be recycled, returning it to the reactants entering the FC. Tube or planar humidifier layout and the humidifier membrane quality determine the humidifier's properties. Important design parameters are gas residence time and water diffusion time (water permeability) from the membrane surface at different temperatures, pressure loss, weight as well as overall size. [Huizing, 2007; Fumatech, no year]

Bipolar plates uniformly distribute gaseous fuel and air, conduct electrical current from cell to cell, remove heat from the active area and prevent leakage of gases and coolant. They significantly contribute to the volume, weight and cost of PEMFC-stacks. The materials include non-porous graphite, coated metallic sheets, polymer composites. [Jörissen et.al., 2013, p. 262] Plate assemblies can be made with good quality and strength at thicknesses well below 2 mm, but flow fields are still limiting. At high current densities much higher gas and liquid water fluxes must move through the channels. A significant gap remains with respect to joining/sealing methods, as well as corrosion protection coating technology and production cycle times. [AFCC, 2015, p. 14] The **Membrane Electrode Assembly (MEA)**, see *Figure 4-48*, consists of the PEM, the catalyst layer and bipolar plates/ electrodes. MEAs are the core component of an FC and their development includes proprietary manufacturing processes and quality control.

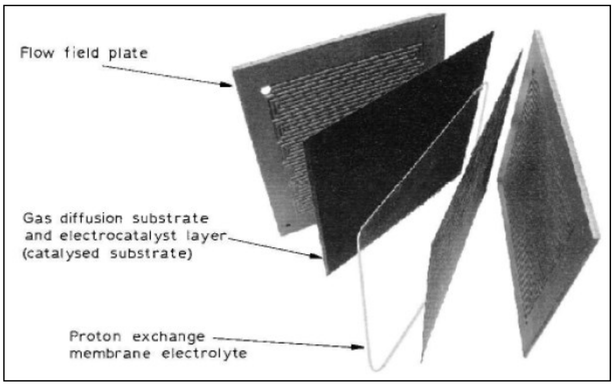

Figure 4-48: Membrane electrode assembly of a PEMFC [Jianyi, 2011, p. 3]

Under ambient conditions, the anode and cathode require **an catalyst** to promote oxidation and reduction reactions. Platinum dispersed on a carbonaceous support is currently the widest used catalyst for H_2PEMFCs. Platinum has a large activity toward the HOR at the anode; a lowering of the Pt-loading of the anode from today's 0.2-0.4 mg Pt/cm² down to 0.05 mg Pt/cm² is realistic. The cathodic ORR, in particular the oxygen splitting, is much more difficult and lowering the Pt-cathode loadings of ca. 0.4 mg Pt/cm² is limited by the poor activity of Pt for the ORR. *Figure 4-49* depicts the DOE targets for PEMFC Pt-loadings. Other studies calculate with a Pt-loading of 0.15 mg/cm², 300 cm² active area per MEA and 350 MEAs per FC stack, i.e. a Pt-need of 16 g/FCV once k300 FCVs are produced. [Bernhart et.al., 2014, p. 15] The current GM Equinox model uses 90 gPt/FCV, the next generation model will include about 30 gPt/FCV and GM develops systems with 10 gPt/FCV. This is in the range that some of the conventional power trains use for the exhaust gas cleaning system today. Current costs of Pt are 35 €/gPt.[152] The

[152] About k4 different catalyst types are available on the market; the Pt-content varies according to manufacturer, type, engine variant and motorisation, year of manufacture and size. As a rule of thumb, the larger the engine capacity, the higher the precious metal load. EU manufacturers use more precious metals than non-EU manufacturers. The year of construction determines the type of precious metals used. Currently, Palladium (22.22 €/g) is cheaper than Platinum, thus more Palladium is used in petrol

Pt-PEMFC catalysts are very sensitive to fuel impurities. CO binds strongly to Pt-sides, reducing the number of reaction sites available to hydrogen poisoning the catalyst. Therefore, the CO-concentration in the fuel has to be less than 50 ppm. [Viswanathan, 2007] Carbon supported Pt-catalysts have nearly reached their maximum. [AFCC, 2015, p. 14] Three new classes of ORR catalysts have been developed, for example:

Pt-based catalysts (alloys or intermetallic) with lower Pt contents: Pt-M catalysts (M= Co, Ni, Cr, Fe, Mo, Bi, Mn) having 3-5 fold better kinetics than pure Pt. For example, (M=Ti, Fe, Mn) enhance the cell voltage by 20-40 mV at a practical current. Monolayer Pt/M core-shell catalysts (M= Pd, Au etc.), e.g. Pt/Pd improves the overall efficiency of the ORR by 33%. **New generation chalcogenides**[153] use Ru-Mo sulphide, selenides. Non-precious metal/ heteroatomic polymer nanocomposites use Fe and CoN_4 macrocyclic compounds. [Jianyi, p. 13-14, 17] In particular, **carbonorganic catalysts** may make a breakthrough in the quest for inexpensive and efficient FC catalysts. New research shows that all-organic catalysts based on nitrogen-doped carbon nanotubes could catalyse the splitting of oxygen just as effectively as platinum, but many questions remain regarding the mechanism and efficiency of catalytic processes that occur at the defects where nitrogen atoms have replaced carbon atoms in the carbon nanotubes.[154] During the development of new catalyst systems it is necessary to simultaneously develop the processes to synthesise them at low cost and possibly to deposit them directly onto MEA with as few intermediate steps as possible to ensure high material yields. [AFCC, 2015, p. 14]

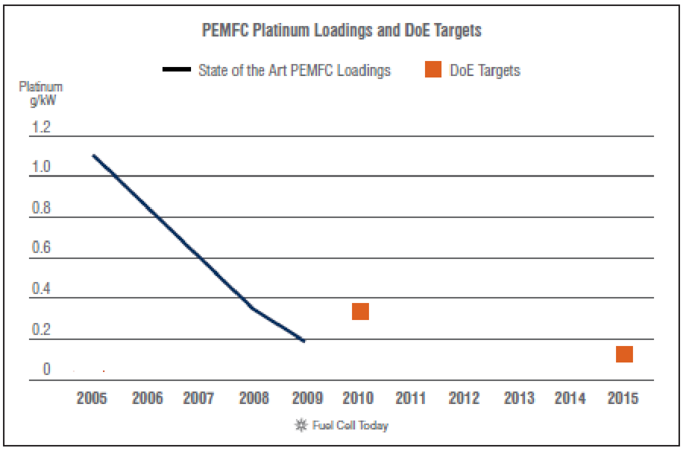

Figure 4-49: DOE targets: PEMFC Pt-loadings [FuelCell Today, 2011, p. 31]

The Pt-demand has been estimated to increase 1.6-fold by 2030 due to the use of new technologies, mainly catalysis and FCs. In addition, the demand will grow due to the growth of the world's economy. Platinum production is highly concentrated to a few countries such as South Africa, Russia, Canada, Zimbabwe and USA. However, during recent years the Pt-price has been quite stable. The contingent resources are large (about 0.1 Mt) and the resources would be sufficient for another good 190 years. Germany covers 45% of its Pt-demand by recycling. [Angerer et.al. 2009, p. XII, 289-290]

Theoretically, an FC could make use of 100% of the reaction enthalpy. Practically, stack efficiency is a function of load and is usually highest at light load (15 to 20% of maximum output) and declines at high load, see *Figure 4-50*. Peak efficiencies of about 68% to 70% are achieved at low pressure (Hyundai's FC-system operates close to atmospheric pressure),

engines. Diesel engines use mainly Platinum due to lower exhaust gas temperatures. Rhodium is used in a constant share together with Platinum in a share of 1 (Rh) : 5 (Pt). A Euro 4 petrol engine catalyst bears an average load of Pt-group metals (Pd, Pt, Rh) of 1.81-5.89 g (<1.4 - >2 l engine capacity), a diesel engine catalyst of 4.75-8.55 g (<1.4 - >2 l engine capacity). New engines include up to 15 g, but data is difficult to obtain because scrap dealers are the major source of data. [http://www.edelcat.de/-ankauf.php; Lucas, 2011, p. 33; http://www.finanzen.net/rohstoffe/platinpreis/euro; http://www.cnet.-com/news/with-toyota-in-its-rear-view-mirror-gm-talks-fuel-cell-car-technology/; 31.08.2014

153 A chalcogenide is a chemical compound consisting of at least one chalcogen ion (all group 16 elements, in particular sulfides and selenides) and at least one more electropositive element.

154 http://www.sciencedaily.com/releases/2012/10/121005082544.htm, 27.11.2012

but with higher boost pressures peak efficiencies are one to two percent lower at light loads (most manufacturers work at approximately 0.2 MPa, increasing output and current density). At full load, modern stacks have an efficiency of 54% to 55% which is, again, lower than for stacks operating at low pressure (57% to 58%). **Cycle average efficiencies on the NEDC or the Japanese test cycle were stated to be in the 60% to 63% range**. [Greene et.al., 2013, p. 5, 8] The exact shape of the voltage-current density-curve (swing) depends on the technology used. For example, the voltage of Hydrogenic's 32 kW stack drops from initial 130 V to 80 V at full current. This is a loss in power of 40%. For comparison, current $LiFePO_4$ batteries have a quite low power swing of around 10%. This relationship has important implications for the FCV-operation: for more power, additional FC-capacity or an energy storage system are necessary. This may disqualify the use FCs in HDVs, which need to provide sufficient power at high loads. [Gillingham, 2007, p. 7-8] The mechanism of FC degradation has been extensively researched and the main causes are corrosion of the carbon anode/cathode and the dissolution of platinum. It is countered with technologies known from exhaust gas cleaning.

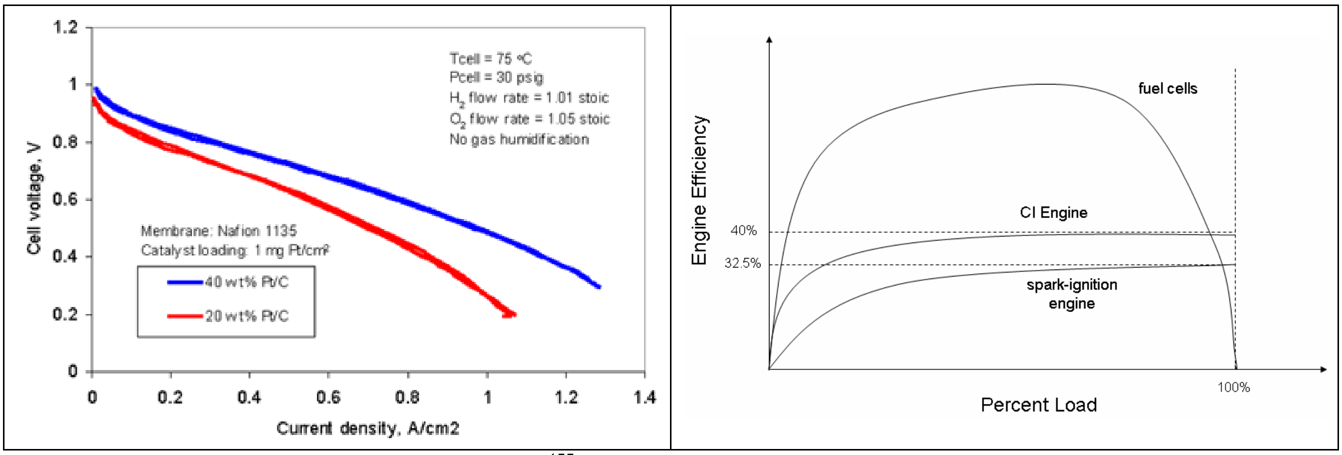

Figure 4-50: MEA performance curve[155] *and engine efficiency versus load for FCs, compression- and spark-ignition engines* [Gillingham, 2007, p. 20]

Demand for development: FC-systems marketed in 2016 are expected to show specific power levels of 2.15 to 2.2 kW/kg and 2.8 to 2.9 kW/l. Currently, improvements between stack generations appearing every 5 to 6 years are about 15% with decreasing tendency per generation. The platinum content of stacks has been greatly reduced over the last decade. While platinum loadings for an 80 to 90 kW FC stack were over 200 g prior to 2001, loadings declined to below 100 g by 2005 and are currently at around 30 to 35 g. [Greene et.al., 2013, p. 7]

FCVs have achieved good performance, safety, comfort and cold start properties. Range, reliability, longevity and package/weight will be further improved when vehicles are brought to market as planned in 2015. **FC-cost and refilling infrastructure both remain the challenge**: Cost reduction could be achieved in addition to increasing production volume by improving the overall design and technology. This includes reducing the platinum loading. However, also more conventional measures are possible. Roughly half the cost of FC-systems is in the Balance of Plant (BoP) which includes water and heat management systems, hydrogen pumps and air compressor/expanders. The BoP of earlier FC systems has used specialised, purpose-designed sub-systems. The trend is to move to commercially available components to reduce costs and to simplify the BoP-system. For example, the next generation stack design from Toyota will be targeted at eliminating the need for a separate

155 http://fuelcell.com/product-category/pem-wmea/, 15.11.2015

humidifier for air intake. There is also the need for a suitable onboard fuel tank, typically constructed of high-strength filament-wound carbon fibre capable of withstanding interior pressures of up to 70 MPa. Such storage vessels remain a high-cost component. Toyota is developing its own 70 MPa storage tank technology. [Greene et.al., 2013, p. 9-12; Morey, 2013]

Daimler and other manufacturers are developing smarter designs increasing power density so that the FC-stack needs less active area. Reducing the active area reduces expensive materials. Companies are developing new manufacturing technologies suited for FCs. Current automotive suppliers are excellent in all kinds of traditional manufacturing – machining, stamping, welding, but high volume FC manufacturing involves thin membranes, catalyst ink, new materials and assembly of stacks. In 2010, Daimler established a manufacturing facility to concurrently develop both product and process. In addition, FC component suppliers need to be taught to become automotive suppliers or established automotive suppliers have to be convinced to go into FV-components, e.g. Bosch Engineering has developed an FC energy management unit for off-highway vehicles. [own project data] A reliable supply base familiar with automotive volumes and processes, such as the standard Production Part Approval Process, has also potential for reducing costs. This is essential to the long term viability of FCVs. [Morey, 2013] The biggest drivers for cost decrease stemming from materials are depicted in *Figure 4-51* (according to the AFCC). The lack of refuelling infrastructure is another hindrance to growing an FCV market. The process to open a new station takes 1.5 -2 years after the decision is made.

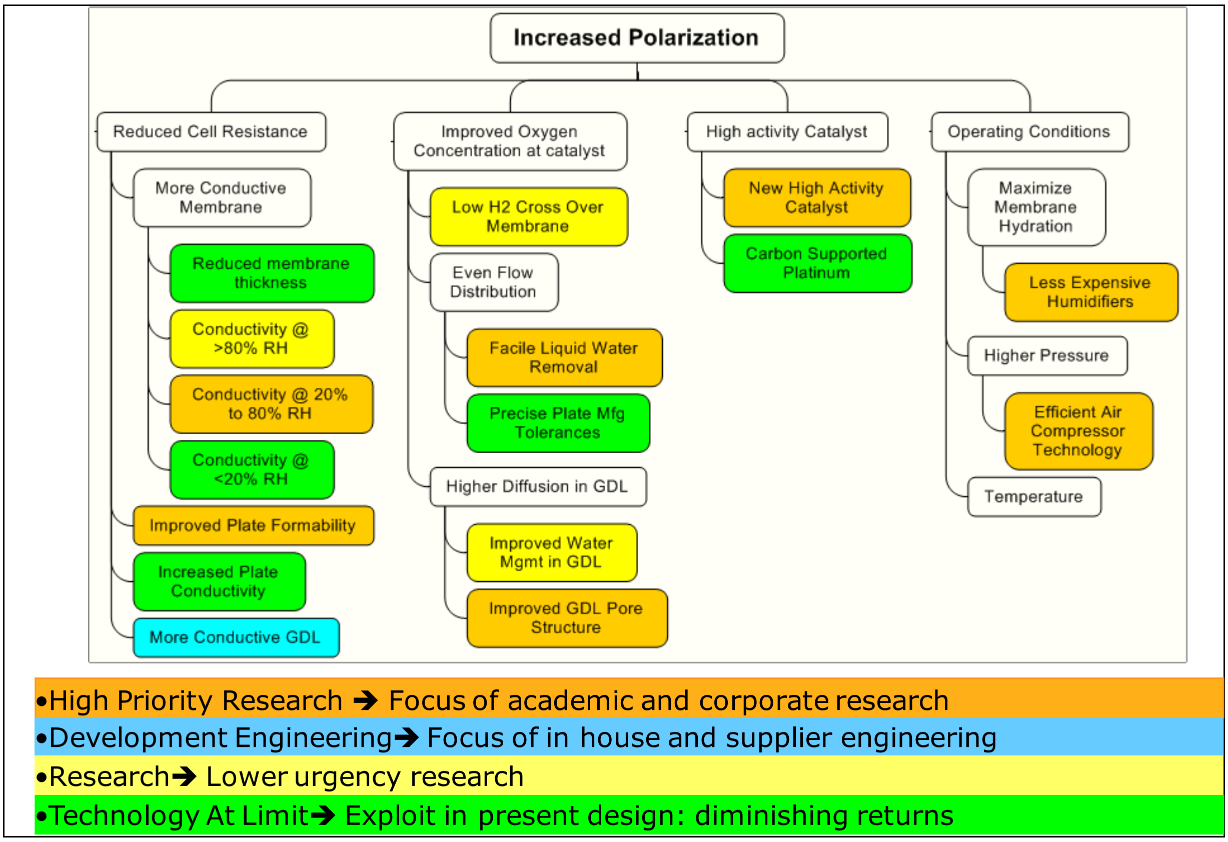

Figure 4-51: The biggest drivers for cost reduction through materials (RH: relative humidity, GDL: Gas diffusion layer) [AFCC, 2015, p. 8]

Currently, three studies (McKinsey, Oak Ridge National Laboratory, Roland Berger, see *Figure 4-52*) are publicly available on FCV and component costs. The cooperative government/industry study, conducted by McKinsey et.al. for NOW and the EC, is the most comprehensive source of manufacturer provided data. McKinsey developed three scenarios on the introduction of electric propulsion systems. However, the impact of the different scenarios on FCV-costs was found not to be significant. The study is ultimately based on a world skewed towards electric power-trains[156]. It is expected that costs for FC components will fall by 90% by 2020 (in Europe: k100 FCVs by 2015, M1 by 2020) and that, by 2030, FCVs will be viable alternatives to conventional vehicles, in particular for larger cars, concerning purchase price and operation costs. [McKinsey, 2010, p. 3, 41]

The technical development needs identified (removing components, operating at a higher temperature in order to simplify the units, reduced platinum use, using alloys and smart catalyst structures, solvent-free electrolyte production with high throughput (dry processes) and moving from batch to continuous production patterns) corresponds to the ORNL study. [Greene et.al., 2013] ORNL compared the costs of the McKinsey study with own investigations and industry interviews and has broken down the figures into components. There is agreement with 2015 FC stack costs because they are based on well understood technical pathways whereas the 2020 costs do not have a recognised technical pathway and therefore uncertainty increases. However, prices depend on technological progress and development of unit figures.

Cost in USD, year, number of vehicles built	**MK 2015, k100**	**ORL 2016 k20/a**	**ORL 2016 k200/a**	**MK 2020, M2**	**RB [157] today**	**RB M5/a**
Fuel cell stack (85 kW)	15,112	24,000	15,150	5,980		
Hydrogen storage (5 kg)	4,080	6,700	5,300	2,040	~12,500	~3,000
Battery (35 kW, 2 kWh)	800	1,500	1,300	696		
Electric motor/inverter/drive (110 kW peak, 60kW continuous)	4,088	3,600	3,150	2,904		
Gearbox		400	350			
Total Power-train	**24,080**	**36,200**	**25,250**	**11,620**	**45,000**	**9,000**
Electric HV-AC/Regener. brakes	540	800	750	240		
Glider	9,108	11,000	11,000	9,108		
Total FCV cost	**33,728**	**48,000**	**37,000**	**20,968**		

Figure 4-52: Analysis of McKinsey and ORL cost figures (1 € = 1.25 USD) [Greene et.al., 2013, p. 15]

Roland Berger also analysed future FC-costs. Today's costs are given as 45 k€; a share of 35-45% is made up by the MEA. 90% of MEA costs stem from materials, mainly PEM and Pt. The study showed that, in a production scenario of M0.3 FCVs p.a., MEA could be produced with current technologies for 7 €/unit, i.e. 2,450 € (350 units/FCV). The costs could be reduced to 3 €/unit with improved MEA and production technology. [Bernhart et.al., 2014]

McKinsey (2010) sees the C/D vehicle segment as the first segment where FCVs will become cost competitive. Future FC-system costs for these middle to upper class vehicles should reach 16-98 €/kW between 2030 and 2050 with FC stack durability between 0.25 and 0.29 Mkm. These cost estimations use learning rates for the period after 2020 which are conservative and considerably lower than historical improvements of comparable technologies, such as wind, solar PV or LNG, see section 5.4. By 2020, the purchase price of FCVs will be still 30% more than that of ICEs and 6.5% than that of BEVs (see *Figure 4-53*), but public incentives on vehicles, fuel, legislative forces and an attractive customer value proposition could be sufficient to bridge this cost gap. (All vehicle purchase prices may vary

156 25% FCVs (M50 FCVs), 35% BEVs (M70 BEVs), 35% PHEVs (M70 PHEVs), 5% ICEs (M10 ICEs), assuming the same European vehicle fleet size as today)) by 2050.

157 Differing assumptions: 90 kW system

according to market conditions, car manufacturers and branding strategies, with a whole range of purchase prices within any car segment – from lowest cost to premium vehicles.)

However, predictions about future trends in technology and energy costs within a timeframe of 50 years are difficult since the impact of technology leaps in any of the analysed propulsion systems is uncertain. Thus, costs in *Figure 4-53* may be read as one possible scenario.

2020 – C/D Segment

Vehicle	Purchase price	Maintenance	Fuel cost	Infrastructure	TCO
FCEV	30.9	4.5	5.6	2.7	43.8
BEV	28.9	3.7	3.4	2.5	38.5
PHEV	26.8	4.9	3.8	1.4	36.9
ICE - gasoline	21.4	5.5	4.7	0.6	32.3
ICE - diesel	21.9	5.7	4.7	0.5	32.8

2030 – C/D Segment

Vehicle	Purchase price	Maintenance	Fuel cost	Infrastructure	TCO
FCEV	25.7	4.2	5.2	1.4	36.5
BEV	26.3	3.6	3.2	2.5	35.6
PHEV	25.0	4.9	3.7	1.4	35.0
ICE - gasoline	21.1	5.4	5.3	0.6	32.3
ICE - diesel	21.6	5.6	5.2	0.5	32.9

2050 – C/D Segment

Vehicle	Purchase price	Maintenance	Fuel cost	Infrastructure	TCO
FCEV	23.7	4.0	4.0	1.1	32.8
BEV	23.5	3.5	2.8	2.5	32.3
PHEV	23.5	4.8	3.6	1.4	33.3
ICE - gasoline	20.5	5.1	5.8	0.6	32.0
ICE - diesel	21.2	5.4	5.8	0.5	32.9

Figure 4-53: Development of TCOs in the C/D-segment, ct/km [McKinsey, 2010, p. 40-41][158]

However, BEV and FCV-technology bear more innovation potential than the mature[159] ICE-technology. McKinsey, assumed that the advantages of lower operational costs of EVs may start to close the TCO-gap despite the high purchase costs with ICEs by 2030. In 2030, TCOs of EVs will be 3-4 ct/km higher than ICE TCOs. Even more, by 2050 all EVs shall be cost-competitive with ICEs: FCVs will be a low-cost solution for larger cars. BEVs are economic for smaller cars and shorter trips while FCVs perform best for C/D and J segments (medium and larger cars) and longer trips. FCVs score almost as well as BEVs on annual driving distances of 10-20 k-km in the A/B (small car) segments. As medium/larger vehicles

158 1 Includes production and distribution cost, 2 Includes retail cost, NOTE: Assuming 15 year lifetime, annual driving distance of 12,000 km, no tax (e.g., fuel excise, VAT)

159 A **mature technology** shall be defined as a technology that has been in use for long enough that most of its initial faults and inherent problems have been removed or reduced by further development. One of the key indicators of a mature technology is the ease of use for both non-experts and professionals. [Theodorou, S. C. et. al., 2011, p. 2619] Mature products have been produced in very large quantities and managed to gain a relevant market share. The Commission has drafted guidance on public intervention in electricity markets in order to minimise distortive impacts. This guideline defines: Subsidies for mature or deployed energy technologies (i.e. with a share of at least [1-3%] in electricity production at EU level), including those for renewable energy, should be phased out entirely in the 2020-2030 timeframe. Subsidies for new and immature technologies (less deployed, with significant potential to contribute cost-effectively to renewable energy volumes) would still be allowed. Mature technologies have a smaller potential for efficiency improvements through learning. Mature technologies follow an evolutionary path; for non-mature technologies revolutionary gains are still possible. [EC, DG Competition, 2013, Art. 119] In analogy, a vehicle technology shall be defined being mature if it reaches a share of 3% in the vehicles in use in Germany.

with above average driving distance account for 50% of all cars, but 75% of CO_2 emissions, FCVs are an attractive abatement option for a large proportion of the car fleet.

The US DOE orientates its recent 2012 FC development targets towards becoming competitive with the ICE. *'The cost of FC power systems must be reduced before they can be competitive with gasoline ICEs. Conventional automotive ICE power plants currently cost about $25-$35/kW (August 2011); a FC system needs to cost less than $30/kW for the technology to be competitive. [...] FC power systems will be required to be as durable and reliable as current automotive engines (i.e., 5,000 hour lifespan [150,000 miles equivalent] with less than 10% loss of performance by the end of life) and able to function over the full range of external environmental conditions (-40° to +40°C).'* The costs targets (see *Figure 4-54*), would need another halving of the 2020 McKinsey scenario costs, see *Figure 4-52*. [DOE, 2012, p. 10-11] They may be achieved using synergies from the development of HEVs and BEVs as well as FC specific achievements from micro and stationary applications.

Characteristic	Units	2011 Status	2017 Targets	2020 Targets
Energy efficiency[160] @ 25% of rated power	%	59	60	60
Power density	W/l	400	650	850
Specific power	W/kg	400	650	650
Costs[161]	USD/kW$_{el}$	49	30	30
Cold start-up time to 50% of rated power				
@–20°C ambient temperature (at)	seconds		30	30
@+20°C ambient temperature	seconds	<10	5	5
Start up & shut down energy[162] from -20°C at	MJ	7.5	5	5
from +20°C ambient temperature	MJ	-	1	1
Durability in automotive drive cycle	hours	2,500	5,000	5,000

*Figure 4-54: DOE technical targets for automotive applications: 80-kW$_{el(net)}$ FC-system operating on direct hydrogen (*Targets exclude H_2-storage, power electronics and electric drive*) [DOE, 2012, p. 17]*

Synergies from development of HEVs/BEVs: FCV-technology benefits in particular from HEV/BEV's energy, control and electric propulsion system developments and from the provision of electric components such as transformers, motors and other components. The availability of reliable series components which can be mass-produced at low cost is crucial to FCV-application. FCVs and HEVs both need low cost e-drive components. Around 30% of technology improvements in BEVs and PHEVs also apply to FCEVs and vice versa. [McKinsey, 2010, p. 5-6] These may be:

- Highly integrated drivetrains (converters, inverters and electrical motors),
- High-energy-density battery systems based on innovative Li-Ion technology,
- Comparative investigation of different electrical storage systems (battery/supercaps) and the respective e-storage management,
- Investigation on vehicle requirements, subsystems and components,
- Vehicle control strategies, energy management and modular system control software.[163]

160 Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.
161 Cost projected to high-volume production (k500 systems per year).
162 H_2 fuel energy (Lower Heating Value) to include the fuel energy required to account for the electrical energy consumed from cold start.
163 http://ec.europa.eu/research/transport/projects/items/hysys_en.htm, 18.11.2012

Synergies from other FC applications: FC technology and component development also takes place for non-automotive purposes such as material handling, stationary applications or special small applications (APU) etc. Stationary FC-technology is in the stage of early market development, because the technology is easier to handle due to fewer restrictions concerning space and weight and can be used as a combined heat and power plant in households or as small power plants. A newly published study by and LDVs applications.[164] More concrete, the residential micro-CHP market targets to M1.4 units (200-750 W_e) by 2020, see section 5.3.1.2.

In conclusion, it has become increasingly evident that the lack of infrastructure and FCV-costs are the main barriers to successful market introduction of FCVs. The development of an appropriate infrastructure is more an organisational problem, because the necessary technology is available and the costs are manageable. The investment costs for 1,000 H_2-stations in Germany would be less than 1 G€. The price target for H_2-fuel (transported and dispensed) is set by the EC and DOE to less than 4-5 €/kg, thus less than 4-5 €/100 km (without taxes). This is in the range of petrol fuel costs. Thus, cost reduction in FCVs is the main remaining problem which could be achieved by further (costly) R&D in technology and manufacturing improvements as well as learning and other benefits from large-scale production (> k100 FCVs). Finally, FCVs need to be improved, produced, sold and used – also to justify for the infrastructure investments. The price gap between conventional vehicles and FCVs has to be covered for each vehicle sold by the stakeholders (see section 5.3 of the marketing process). These so-called **buy-down costs of the technology** will be huge and will not be shouldered by the FCV manufacturers and the users without legislative pressure and public incentives.

In addition, FC-system serial production will have to be managed by manufacturers. This will require cooperation with the chemical industry and other partners. These business relationships will need time to develop and integration in vehicle production needs to be organised.

164 http://www.luxresearchinc.com/news-and-events/in-the-news/fuel-cell-vehicles-18-billion-market-2030, 15.11.2015

5 The market transformation perspective

The transformation of the car vehicle market towards clean and renewable fuels will be a lengthy process. In Germany, 37.4% of the deregistered vehicles have been older than 13 years in 2014. In general, spare parts of the latest vehicle models are available for 15 years.[165] This is the minimum time for complete market penetration of any new technology. The main influencing parameters for market penetration are:

- **Cycle of vehicle renewal:** Today, there are M43.9 cars in use in Germany, about 3M vehicles are newly registered annually. Even if the introduction of new technologies influences the individual decision to purchase a new car “I want to have it”, the main decision drivers are usually legal, economic or technical criteria or the incentives set by government and others. It is not assumed that the introduction of H_2-fuel will decrease the average renewal cycle significantly simply on the basis that everyone would like to have it.
- **Market penetration rate:** It will be significantly influenced by market forces, the level of market entry barriers as well as incentives set by the government and other stakeholders. However, according to market economy principles, governments should intervene in the economy only when markets fail to allocate resources efficiently and when the intervention will improve net social welfare. These principles do not foresee government interference for the benefit of individual technologies, i.e. reducing their market entry barriers.

The **market** is a virtual or real location where the seller of a service, right or product meets a potential buyer. It is a social structure to facilitate the exchange of ownerships. In a free market the price for goods or services is determined by the law of supply and demand. In an ideal market , see [Bitz et.al., 1993, p. 325], limited resources are allocated efficiently. In reality, the market price quantifies the value of a product to the consumer and thus balances it against other products, too. Hence, a monetised priority order of societal demands emerges; each consumer can compare the intensity of his/her own demand with the demand of society as a whole. However, markets may fail, leading to inefficient outcomes. In economic theory, public goods are known to be one of the main reasons for market failure, because the market is not able to make a party involved a party affected. [Kirsch, 2004, p. 33-36]

A **public good** is a good that is non-rival and non-excludable. The characteristic “*non-rival*” means, that the consumption of the good by one individual does not reduce the amount of the good available for consumption by others. For example, breathing clean air by one individual does not significantly reduce the amount of clean air available to others. Being *non-excludable* means, that it is not possible to exclude individuals from the good's consumption. [Behrends, 2001, p. 82] Market failure in market transactions is often caused when the costs or benefits of externalities involved in the transactions are not accounted for in the price of the product that is exchanged. **Typical externalities of transport** are health or environmental damage, a negative contribution to energy security and the climate, use of public space, etc. In these cases, the logic of the market failure argument calls for an intervention of the government to internalise market externalities and to correct the market failure. [IEA/OECD 2003, p. 64-68] Tradable permits and charge systems are seen as efficient instruments, see section 3.3, [Kirchgässner et.al., 2002, p. 19, 21], which could be implemented by governments to support markets that would grow if the internalisation of externalities were to be achieved.

However, governments often use so-called ‘second-best instruments’, which do not have the potential to internalise the external effects, but nonetheless support the new technologies,

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165 http://www.kba.de/DE/Statistik/Fahrzeuge/Ausserbetriebsetzungen/ausserbetriebsetzungen_node.-html; 27.07.2014

e.g. subsidies or technology support programmes, see section 4.1. In addition, the EC and the German government set targets for air quality, climate protection and energy security. Ideally, these targets are non-discriminatory, i.e. they do not favour one propulsion system or fuel over another. Second-best instruments are used when a certain intervention in the market may be desirable and the first-best solution is not attainable, e.g. because the related changes are considered to be 'too big' or costly or because of the interference of powerful lobbying groups. [IEA/OECD, 2003, p. 68-69] The introduction of H_2-fuel was selected as a useful measure by the EC and the German government to support their climate and energy targets. The motives for the support of governments for H_2FC-technology are investigated in the following stakeholder analysis. The interests of various stakeholders are considered on the basis of the "Economic Theory of Democracy". This means that the market economy principles are applied to the decision making of the stakeholders, which is not directly market related. [Downs, 1957] The following analysis is concerned with the behaviour and roles of the market actors, how their attitudes guide decisions and how these attitudes can be influenced. It implies a rational perspective of all market actors. The effectiveness of regulatory action, incentives and other measures taken to support H_2-fuel are evaluated in the framework of the Delphi analysis, see section 6.3.

The main actors or stakeholders who are affected by environmental policy are voters, users, government (politicians), bureaucrats in the public environmental administration, etc. and the 'economy' with its different interest groups. [Kirchgässner et. al. 2002, p. 7-19] Thus, the success of the H_2-economy will not solely depend on the performance of the H_2FC-technology, but also on its public acceptance, the public opinion, political and administrational support as well as the behaviour of users, energy companies and the vehicle manufacturers. The technology manufacturers have a double function: they account for the technical performance (a basic requirement), but are also stakeholders in the process with their own interests for succeeding in the market.

In addition, there are several 'external' driving forces and inhibitors for the market development of hydrogen as a fuel. A **market driver** facilitates the market penetration of H_2FCV-technology. A **market barrier or inhibitor** is anything that slows down the rate at which the market for H_2FCV-technology expands, including market failure. The implementation of H_2FCV-technology is a market process. The **chasm of commercialisation** describes the difficult transition from the pilot vehicle to the mass market qualified and mass-production-proven vehicle. It is related with manifold difficulties and very high investment needs which cause the failure of many technologies. The emphasis of the following analysis is on understanding such barriers or drivers and on evaluating under which preconditions there might be a legitimate role for governments to intervene in the market.

The main driving forces may be price of conventional fuels as well as climate and environmental policy. Furthermore, the success of other technologies under development in parallel such as CCS, renewable energies, storage technologies etc. is influencing the market penetration of hydrogen fuel because, in the case of failure in development, these technologies could also become a "braking" force. *Figure 5-1* depicts the conclusion of a 'Conference on the Hydrogen Economy (Brussels, 16.6.03)' raising the questions: *Which drivers have the potential to encourage and to accelerate ../ Which barriers have the potential to discourage and to delay.. .. the realisation of the political vision in Europe?*

The following analysis is carried out in an environment in which the process of H_2FCV-technology establishment is still ongoing even if some decisions already have been made, at least for the mid-term, e.g. ICE- vs. FC-technology, use of LH_2 or CGH_2 at 35-MPa or

70-MPa. The availability of a bundle of technology options bears chances and risks. Drivers and inhibitors are also analysed within the Delphi-analysis.

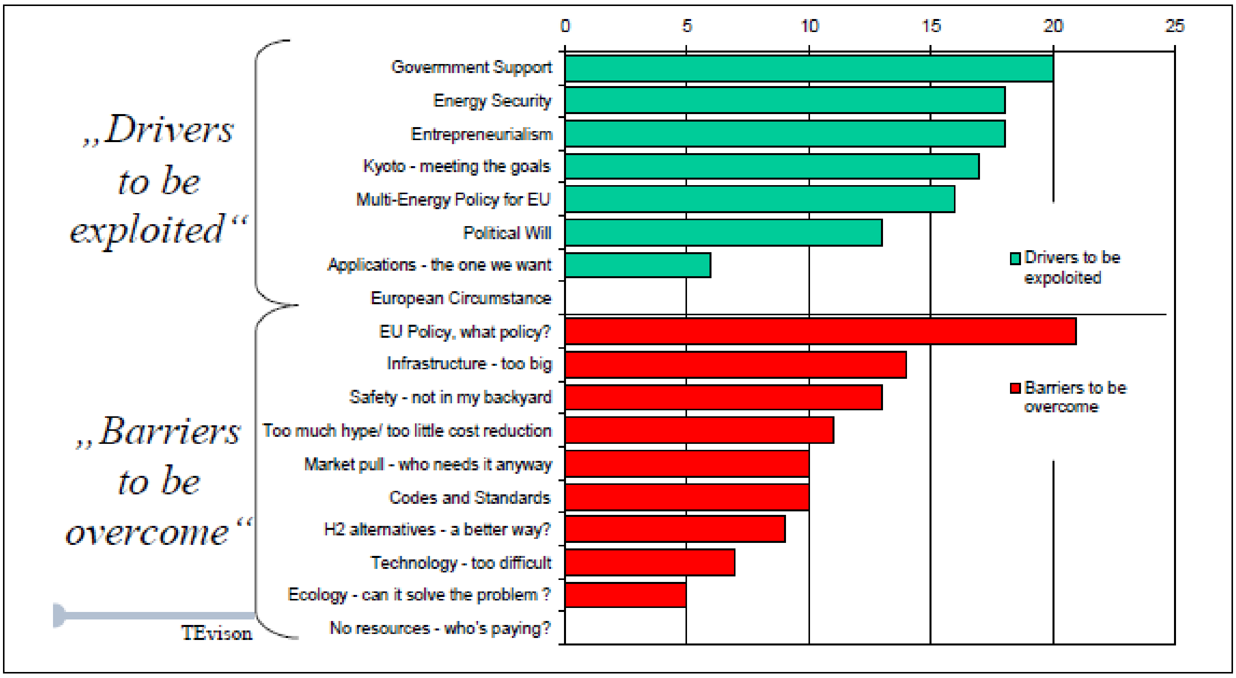

Figure 5-1: Barriers and drivers to H_2-economy implementation [HyNet, 2004, p. 7]

5.1 Barriers to the hydrogen fuel market penetration

Individual barriers to the market introduction of H_2-fuel are overlapping and interacting. In detail they comprise:

New product handicap: Hydrogen fuel and FCVs can be called "new-to-the-world-products"; that means that these products may create an entirely new market and industry. In classical economic theory new products fail because: [Kotler, 1997, p. 308]

- A high-level executive might push a favourite idea through, in spite of negative market research findings. H_2FC technology is far beyond this status already.
- The idea is good, but the market size is overestimated. This seems to be the case with the NEP estimating a market for one million EVs by 2020. Targets of the NIP are more moderate, but still challenging, see section 4.1.2.
- The product is not well designed and does not meet performance expectations: the car has to meet the demands of the EU citizen who typically expects ever-increasing levels of customisation, comfort and safety features in increasingly fuel efficient vehicles. Automotive products must compete on the basis of features and price while simultaneously helping to meet a host of societal goals. There are stringent requirements for safety (e.g. pedestrian protection), clean air, GHG-emissions, reduced dependence on imported fuels etc. [EC, DG Enterprise and Industry, 2006, p. 13]
- Long R&DD phase during which the interest of the public wanes, see section 6.1. In addition, development costs could be higher than expected.
- The new product is incorrectly positioned in the market, not advertised effectively or overpriced. Manufacturers have not yet published details on market positioning and prices for FCV market entry.
- Competitors or competing technologies fight back harder than expected.
- Technology-specific barriers, e.g. lack of filling infrastructure, uncertainty about H_2-production and distribution pathways or safety concerns.

- Institutional barriers such as distorting regulatory and fiscal policies, misplaced incentives and differences in entrance conditions to capital markets. Missing or non-harmonised standards often hamper the market penetration of new technologies.

Immaturity of market and infrastructure: H_2FCV-technologies face a series of "chicken and egg" problems, e.g. the **need for new filling station infrastructure**: H_2-fuel describes not only a new vehicle technology which needs to find its way onto the market. For the refuelling of the vehicles a close network of filling stations needs to be provided. This implies investment and co-operation between various industries because the H_2-economy needs exceptional changes to the infrastructure to be carried by:

- Energy or chemical companies to produce the fuel and to invest in RES,
- Technical gas companies to distribute the fuel and to develop filling and storage technologies,
- Mineral oil companies to sell the fuel, e.g. the consumer expects the full range of services from an H_2-filling station (shop, car wash, tyre pressure check) etc.,
- Vehicle manufacturers to negotiate filling protocols with other industries.

A too low ratio between the number of FCVs and H_2-filling stations is a major hindrance for the market development, because significant turnover and profit from an infrastructural change arise only once economies of scale have been achieved. Similar barriers include the lack of a well-established manufacturing industry, lack of supplier networks and lack of servicing and maintenance facilities and staff.

Individual costs: the implementation of H_2FCV-technology will place an extremely high burden on the vehicle and infrastructure manufacturers and early operators/users. The individual cost-benefit-ratio of the use of H_2FCV-technology needs to be evaluated from the perspective of the individual, i.e. the vehicle user, as the smallest unit of analysis (methodological individualism)[166]. It is assumed that the user endeavours to maximise his own benefit. In a decision situation he will chose the alternative that offers him the highest benefit or causes the lowest costs. The individual user has to expect **several disadvantages** from the new technology, e.g. reduced mileage, top speed and space in the boot as well as increased vehicle mass and therefore reduced load, high investment costs, changes in maintenance and filling routines etc. Consequently, for a successful market penetration, there must be a market pull, i.e. palpable reasons and possibilities for consumers to switch to H_2-fuel. These arguments must be well-made and marketed.

Insufficient and inaccurate information or high transaction costs complicate a purchase decision, e.g. information costs or training needs to use the equipment. The market introduction of H_2FCV-technology needs manifold dedicated awareness building and information to plenty of groups. This includes users, technicians in garages and service points, filling station operators etc. Information has to be serious, not sensational. Furthermore, uncertainty of the amount of fossil fuel still economically available may concern the stakeholders.

Safety concerns: H_2-technology is proven and safe. It has already been applied for decades in industrial applications. However, change generates fear which can only be overcome through public education. Experience must be gained with hydrogen through visible local

[166] According to the Austrian socio-philosopher Karl R. Popper the theory of the methodological individualism means that “alle sozialen Phänomene, insbesondere das Funktionieren der sozialen Institutionen, immer als das Resultat der Entscheidungen, Handlungen und Einstellungen menschlicher Individuen verstanden werden sollte und daß wir nie mit einer Erklärung aufgrund sogenannter ‘Kollektive’ (Staaten, Nationen, Rassen usw.) zufrieden sein dürfen”. Popper, Karl, 1945, (Die offene Gesellschaft und ihre Feinde, Bd. 1, p. 116) quoted from Behrends, Silke, 2001, p. 5

projects to establish greater public acceptance. In addition, safety must not be compromised and there must be a high level of standardisation to improve safety and confidence.

Investor confidence / perceived risk: large investments are typically required both to manufacture new energy technologies and to purchase and install them. Financial institutions and other potential investors need to be provided with good quality information to raise their confidence in the use of more efficient and sustainable H_2-technologies.

Uncompetitive market prices for fuel and vehicles, because scale economies and learning benefits have not yet been realised. This concerns production, distribution and service. **Price distortions** occur, because costs associated with current technologies are not included in their prices. For example, many externalities of car use (costs and benefits) are conferred to third parties. In addition, current fuels and technologies are also not equally treated, e.g. fuel taxes preference of diesel or natural gas. However, H_2-fuel has to compete with these fuels on the basis of current market conditions.

Lack of appropriate regulations, standards and codes: the lack of EU-wide/global codes and standards limits relevant market size and increases launch costs. The existence of agreed standards and regulations support understanding of safety and facilitate planning. For H_2FC-technologies, barriers are created by the inexperience of the relevant authorities, architects and companies' construction departments which hinder the deployment of the technology. Such barriers are tackled by the EU, the industry and lobbying organisations, e.g. NOW published an internet based guideline regarding the licensing process for H_2-fuelling stations. [http://www.h2-genehmigung.de, 15.03.2014]

Lack of policy harmonisation: the markets for new transport technologies are influenced by policies which are designed to support existing vehicle manufacturers and fuel suppliers. A reliable and harmonised legal framework needs to cover at least EU28 (and California), e.g. taxes on H_2-fuel, technology standards for vehicle homologation etc. to deliver the scale needed for profitable market development of a global vehicle business. Any short-term policy cannot deliver the stability within which long-term investment plans are made.

Non-proven practicability of technology in daily life: Practical aspects play a key role in the marketing of advanced transport technology, because primarily, the vehicle applied in any company or private household must be able to fulfil its duty properly at acceptable cost. Demonstration projects can increase user confidence in H_2FCV-technology.

5.2 Drivers to the hydrogen fuel market penetration

The market introduction has to be driven by the advantages of H_2FCV-technology. The **individual technology benefits of H_2-fuel** include the provision of a **clean, efficient, convenient and silent electrical drive suitable also for long distances which may result in reduced energy costs**. FCVs are benefitting, due to hybridisation, from energy recuperation in particular in urban traffic with lots of stop-and-go. The early technology adopter may also generate an image profit as technology pioneer. Other benefits often cited in relation to the use of hydrogen are a contribution to the national energy security and efficiency, to technology and economic development, to road transport emission reduction and to climate protection. These benefits cannot be accounted directly to the individual user. More specific driving factors for H_2-fuel market penetration are:

Government Support: this could include direct or indirect fiscal, legal and financial support to the H_2FCV-technology, see section 3. The German and European funding programmes for clean vehicle technologies are concentrating on electro-mobility, including FCs and H_2-fuel, see section 4.1. Thus, there are fewer funds for other topics such as clean burning biofuels or the optimisation of the incumbent ICE. Nevertheless, the current positive supporting sentiment for H_2FC-technology may change in the public administrations and in the government, if no success stories are written or if serious alternatives arise in the debate.

Entrepreneurialism: the widespread use of renewable H_2-fuel could have big business opportunities. Europe combines the expertise and relevant intellectual capital necessary for innovation development. Several business start-ups have been founded around H_2FC- and electro mobility technology. In particular, the CEP and the H_2-initiative have the potential to substantially manage and promote the market introduction of H_2FCV-technology. These high-level collaborations across industries and between companies is unique in German history and takes the complex situation into account. Currently several other initiatives are emerging to support the H_2-economy, including use of wind energy and large H_2-storage. It is unclear whether these new players are also ready to contribute significant financial resources.

The follow-up to the **Kyoto protocol** and other international treaties may stress further activities to continue with technology development and implementation. In particular, the Kyoto debate led to an increased ecological consciousness in government, industry and public, at least in Western Europe and many developing countries. In Germany, commitment to strategies to combat global warming is widespread; emphasis is placed on minimising local air pollution as well as on sustainable economic activity. More and more companies and products are committing to a small or neutral carbon footprint, e.g. DHL's GOGREEN initiative.

"Multi-Energy Policy for EU": A co-ordinated approach of the EU energy policy combining energy sources and energy carriers (including hydrogen) according to their economic and environmental merits and a long-term vision for the use of renewables and reduction in the exploitation of fossil fuels promote H_2-fuel. The new EC climate targets for 2030 are much more cost orientated. They are heavily negotiated. The rigidity of the debate reflects the seriousness that opponents expect for any consensus to be implemented.

Energiewende: the German word for a turnaround in the energy systems describes the transition to a sustainable economy by means of renewable energy and energy efficiency. This transition requires the build-up of new energy systems, in particular energy storage systems to comply with the German CO_2-targets by 2050. The consensus on the Energiewende has been called into question by different parties. After the 2013 elections, a realignment of the policy started. A social consensus must be found on use of excess wind energy, priority of renewable electricity feed-in, use of H_2-storage technologies or whether other energy efficiency measures should be preferred such as weatherisation programmes. Nevertheless, the transition of the energy system is already on its way. On the one hand, the large profit loss of the bigger energy companies like RWE and EON resulted in a massive staff reduction and closure of power plants. On the other hand, more and more small, decentralised energy suppliers are emerging. In recent years, electricity prices are decreasing on the Leipzig electricity exchange, e.g. the regular price in the second quarter of 2014 was 3.124 ct/kWh compared to III/2012 of 4.352 ct/kWh, resulting in an increasing EEG-apportionment (and higher end consumer prices).[167] In 2010, M0.37 working places were already related to renewable energies in Germany. It is estimated that this number could increase to M0.5-0.6 working places by 2030. [Lehr et. al., 2012, p. 6]

Applications: the ongoing profitable development of niche markets for FC-application in camping, leisure and communication technology demonstrates the technology to the public.

167 http://www.bhkw-infozentrum.de/statement/ueblicher_preis_bhkw.html, 26.07.2014

Technology surrounding: hydrogen will play a role in the new energy system, but other technologies are also viable and will find their place in the new European energy 'mosaic'. Some of these technologies will be a promoter such as the increased use of wind energy; others will be inhibitors, e.g. carbon capture and sequestration may promote the use of fossil fuels. Large-scale and improved H_2-production, storage and distribution technologies will become available during the commercialisation process within the next few years, but successful technology development is not equivalent to successful economic development, thus good value-added chains are necessary.

5.3 Analysis of stakeholders

The stakeholder approach originated from the business sciences. "Organizations have stakeholders. That is, there are groups and individuals who can affect, or are affected by, the achievement of an organisation's mission". [Freeman, R. Edward, 1984, p. 52] Stakeholders in a change process may be persons or organisations with a declared or conceivable interest. Executives must take multiple stakeholder groups into account to be successful and also political and environmental programmes need to manage their stakeholders to effectively implement changes. In consequence, stakeholder analysis has evolved into economics, political science, game and decision theory and environmental sciences.

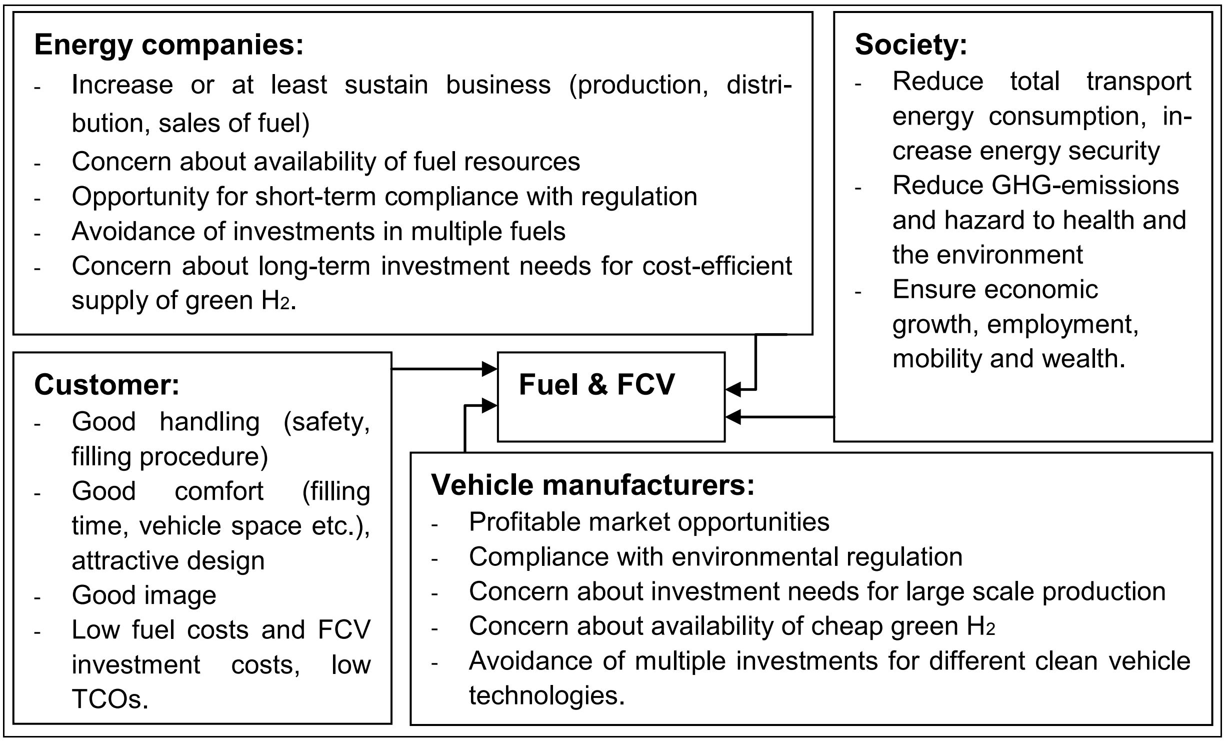

Figure 5-2: Stakeholders and their interests [Adapted from VES 2007, p. 40 ff.]

Stakeholder analysis is a process of understanding: *Who the stakeholders are and what their perceived stakes* are, i.e. the systematic gathering and analysis of information on those who have a 'stake' or an interest. It should be considered when developing or implementing a policy, programme or market. In detail this includes stakeholders' interests in H_2FCV-technology, their position for or against H_2-fuel and their ability to affect positively or negatively the marketing process (through power and/or leadership). Information on *the processes and relations between the stakeholders* includes knowledge on the (potential) alliances between stakeholders and *how these could be implicitly or explicitly be managed* to support the marketing target. Information gained from stakeholder analysis supports the design of efficient policy actions and programmes for market introduction of H_2-fuel. It allows to estimate, if measures adopted are politically realistic and sustainable. The general interests of the main stakeholder groups are summarised in *Figure 5-2*. The main stakeholders in the market introduction process of H_2-fuel are:

- Vehicle and component manufacturers,
- Energy and mineral oil companies as well as the chemical industry,
- The government and the public,
- Customers, i.e. individuals and fleet operators.

5.3.1 The manufacturing industry

5.3.1.1 Automotive industry

The European automotive industry is being subject to significant societal demands and is facing a large globalisation challenge, in particular from emerging and lower-cost economies in Asia. This competition is mainly cost competition. European companies focus on innovation and have sought to achieve economies of scale by standardising parts across their incumbent model ranges and by producing more models from fewer platforms to face this competition. The largest platforms such as Toyota MC-M and Volkswagen PQ35 achieve annual production figures of more than M3 vehicles. [Meiners, 2012, p. 74] However, the geometry of an advanced technology vehicle does normally not fit on standardised, existing platforms, which complicates market entry.

The OEMs manage highly complex R&D programmes which are focusing, among FC-technology, on BEVs and advanced ICE-technologies by increased co-operation. Several cooperative arrangements between FC or battery manufacturers and OEMs are already in place. Furthermore, some OEMs are currently building up partnerships with infrastructure suppliers, see section 4.1. Individual players are described below:

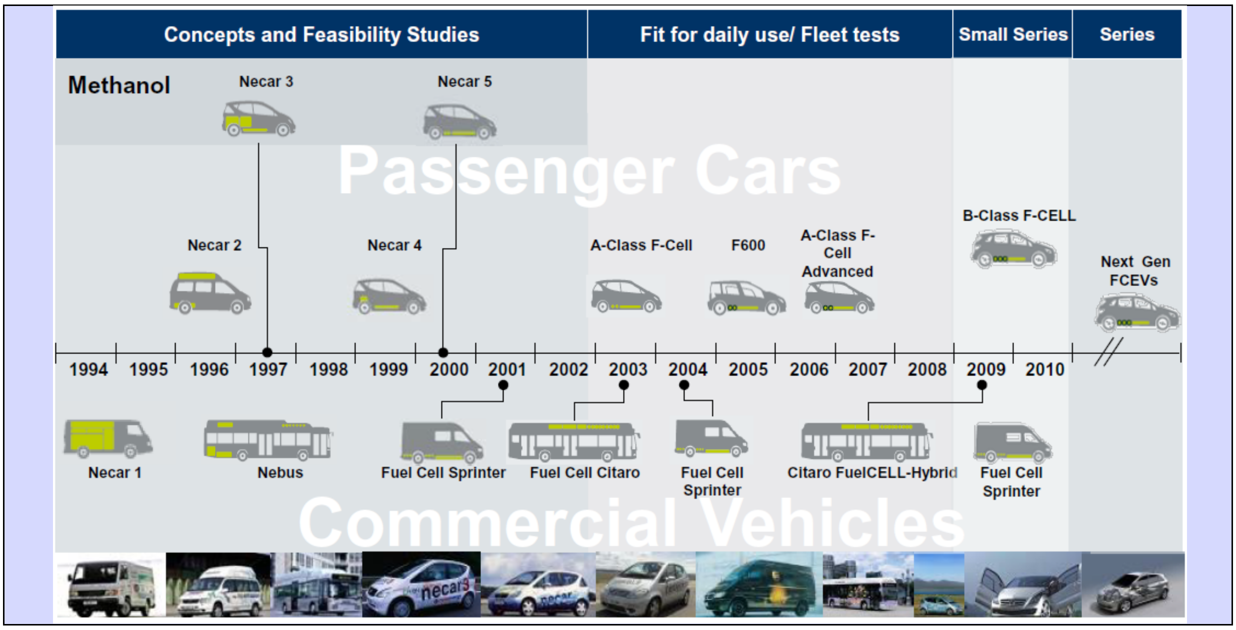

Figure 5-3: History of Daimler FCVs [Friedrich, 2012]

Daimler: ranks 14th of the world's largest manufacturers. In 2013, Daimler produced M1.782 vehicles. Daimler has almost 20 years of experience with FCVs. In 1994, the Necar 1 was presented. It was followed by around 20 FCV-prototypes. In 2002, production of a limited number of the A-class F-cell was started. This delivered first production experiences. The

FCVs covered over M4 kilometres. The B-class F-cell and the FC Citaro bus are already available to fleet customers in Germany. 200 F-Cells are made available for leasing in Europe and the United States. Daimler aims to make vehicles cost competitive with conventionally powered vehicles and continues to work closely with partners from the government, energy providers and other automobile manufacturers to ensure that a sufficient infrastructure is on hand to support the FCV-commercialisation in the next few years, see *Figure 5-4*.[168] Daimler has been a founding member of the VES, the CEP and the H_2-Mobility initiative. It is also a member of the Californian Fuel Cell Partnership (CaFCP).

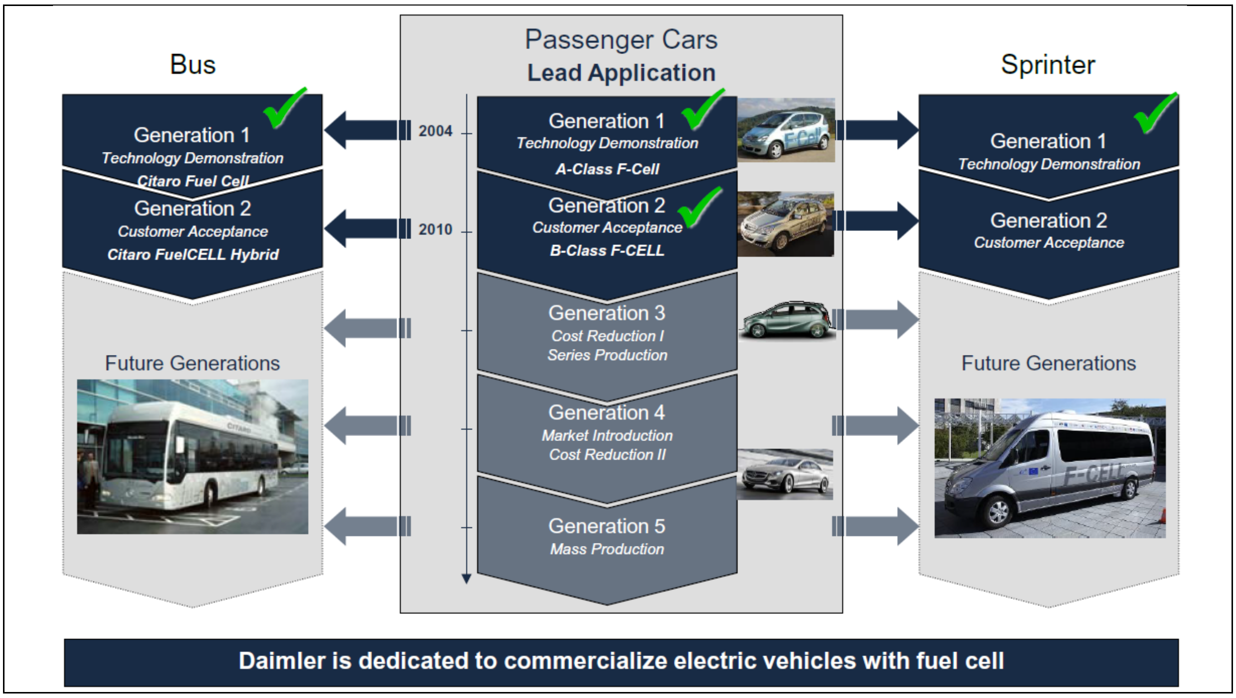

Figure 5-4: Daimler's Fuel Cell Technology Roadmap [Friedrich, p. 15]

Toyota is the world's largest vehicles manufacturer. In 2013, Toyota produced M10.3 vehicles. Toyota is a CEP-(since March 2010) and CaFCP-member. Toyota states that FCs represent the most promising next-generation power source. In 2002, Toyota started the commercialisation of its Fuel Cell Hybrid Vehicle (FCHV) using the full hybrid technology known from the Toyota Prius, the first HEV produced in large series. In 2010, 18% of Toyota's Japanese production were of the Prius model (M2.98 cars). Toyota develops own FC-stacks. The current stack has an output power density of 3 kW/l. Toyota and its subsidiary Hino Motors announced to launch an FC-bus by 2016.[170] In 2013, Toyota formed an alliance with BMW. Toyota expects FCVs to be cost competitive

Figure 5-5: Toyota sedan-type FCV scheduled for launch around 2015[169]

[168] In the following, all vehicle numbers used for company ranking do not include Chinese companies. http://www.oica.net/wp-content/uploads/ranking-2013s-2.pdf; 12.05.2015, http://cafcp.org/about-us/-members/daimler; http://www.cleanenergypartnership.de; 21.01.2014

[169] http://www.fuelcelltoday.com/news-events/news-archive/2012/september/toyota-announces-fuel-cell-vehicle-progress-plans-to-launch-fuel-cell-bus; 22.01.2014

[170] http://cafcp.org/about-us/members/toyota; http://www.cleanenergypartnership.de; http://www.fuelcelltoday.com/news-events/news-archive/2012/september/toyota-announces-fuel-cell-vehicle-progress-plans-to-launch-fuel-cell-bus; 22.01.2014

with incumbent technology by 2030. The dramatic reductions in FC-costs shall help to sell annually between k5-10 FCVs once the FCVs goes on sale in 2015.

The cost for a 2007 FC-system was almost 750 k€. An FCV sales price of 72 k€ was announced in 11/2013. In 06/2014 the sales price of the new 'Mirai'-FCV was announced to be 51 k€. Even more, Toyota is planning to lower the FCV-price to around 3-5 M¥ (22-36 k€) in the 2020s to boost sales and expand annual production capacity. The FC stack cost has been lowered by reducing the amount of platinum in the catalyst, reducing the stack's size saving installation space and sharing components with existing hybrids, including a motor and electronics. However, the FC-sedan will not share a platform with the next-generation Prius, because the FCV is heavier and has a different underbody structure and layout. The four-seat FCV rides on an FC-platform with two high-pressure H_2-tanks and has a range of about 700 km. Toyota Motor has started the commercial production of H_2FCVs in mid-December 2014 and is considering manufacturing dozens of the vehicles per month at its Motomachi plant in Toyota, Aichi Prefecture. Toyota intends to launch its FCV sedan in Japan, North America and Europe. In Europe, the first markets likely to have the car are Germany, the Scandinavian countries and the UK.[171]

Honda Motor: in the ranking of the world largest manufacturers Honda takes 8th place. In 2013, Honda produced M4.3 vehicles. Honda has been a CaFCP-member since 1999 and a CEP member since 2011. In 2002, Honda became the first automobile manufacturer to lease a government certified FC-car for daily commercial operation on public roads. On that day, the first of five FCX's became part of the City of Los Angeles' fleet. In 2005, the FCX became the first ever FCV leased to an individual customer. The FCX comprises a Honda designed and engineered FC power system and a compact, high torque drive motor combined with a Honda developed Ultra Capacitor improving acceleration and energy efficiency by braking energy recovery. In 2008, Honda began limited production of an all new FC car, "FCX Clarity" targeted primarily at leasing to private individuals. It features a Honda 100 kW "V-Flow" FC stack and a Li-ion battery. Honda is continuing to research solutions specifically for at-home H_2-refuelling of FCVs ('Home Energy Station' project in Torrance, California).[172]

Hyundai-Kia was the 4th largest vehicle producer with M7.233 vehicles in 2013. It unveiled its first Hyundai SUV with an internally developed FC-stack in 2000; both methanol- and H_2-fuelled variants were demonstrated. The 2004 Hyundai Tucson FCEV and Kia Sportage FCEV had improved ranges using UTC Power FCs. Hyundai-Kia returned to demonstrating its own FC-technology with the 2008 Kia Borrego FCEV, the predecessor of the current Hyundai ix35 FCEV, which was first revealed in late 2010. The company has targeted producing about one thousand of these vehicles for lease between 2012 and 2014 (anticipated in 2012), before entering full commercial production with a k10-unit full-scale production run planned for 2015.[173] In 2012, Hyundai signed an MoU with the Norwegian firm HYOP to supply ix35 FCEV to public agencies, commercial fleets and taxi firms in Norway. In the longer term, Hyundai-Kia plans to use the Kia brand to sell smaller BEVs and the Hyundai brand to sell larger FCVs. [FuelCell Today, 2013 (2), p. 18] In May 2014 Hyunday announced that "*Tucson Fuel Cell SUVs began rolling onto US soil, marking the first delivery of a mass-*

171 http://europe.autonews.com/article/20131211/ANE/131209875/toyota-targets-5000-to-10000-fuel-cell-sales-a-year#axzz2nzZQXxx0, http://fuelcellsworks.com/news/2014/06/04/toyota-motor-corp-plans-to-begin-commercial-production-of-hydrogen-fuel-cell-vehicles-in-mid-december/, http://www.boulevard-toyota.com/en/articles/toyotas-fuel-cell-sedan-to-be-ready-in-late-2014-not-2015/5563513307-d1e812002d85ac/, 17.08.2014

172 http://automobiles.honda.com/fcx-clarity/home-energy-station.aspx; 9.04.2013

173 http://www.fuelcelltoday.com/news-events/news-archive/2012/april/exclusive-hyundai-motor-company-clarifies-fuel-cell-car-commercialisation-plans, 22.01.2014

produced fuel cell vehicle for the U.S. market. The first retail sale of the Tucson Fuel Cell is expected within the next several weeks in Southern California." Hyundai offers a free fuel 499 USD/month lease deal in California.[174]

GM is the second world's largest vehicle manufacturer. In 2013, GM produced M9.629 vehicles. GM has also a long history in FCV-development. GM has developed its own FC stack system. GM is a member of the CaFCP and Opel is a member of the CEP, GM invested over 2.5 GUSD in FC-technology. GM's record of FC technology leadership comprises[175]:

- 1968: World's first operational FC-powered vehicle,
- 1997: First GM FCV propulsion concept – Geneva Motor Show,
- 1998: First GM drivable FCV (methanol powered) – Paris Motor Show,
- 2000: First GM direct hydrogen FCEV; set 15 endurance and speed records,
- 2001: World's first FCEV with full functionality,
- 2006: FCEV to demonstrate 300 mile range in real world driving conditions,
- 2007: Project Driveway Launch provided 119 converted Chevy Equinox FCVs to private citizens and agencies in three US and other, international cities,
- 2010: GM introduction of 'NextGen'-technology power module,
- 2013: GM closed its FC research facility in Honeoye Falls, NY and consolidated its FC-program to capitalise on "synergies" with its Global Powertrain Engineering headquarters,
- GM is considering commercialising FCVs such as the Chevrolet Equinox by 2015/16.[176]

Ford: in the ranking of the world's largest manufacturers Ford is in 5th place. In 2013, Ford produced M6.077 vehicles. Ford is a member of the CEP. Ford has been working with H_2-fuel since the beginning of the 1990s. In 1998, Ford presented its first FCV, followed by several more prototypes. The FC Ford Focus (fifth generation) was delivered to pilot customers in 2004. The Ford Edge is an electric vehicle, comprising an FC range extender charging the Li-ion battery during driving.[177]

Nissan is the sixth largest vehicle manufacturer in the world. It produced M4.95 vehicles in 2013. Nissan only released its first fleet of demonstration vehicles in 2003. The X-Trail SUV fitted with UTC Power FCs was leased to a number of Japanese customers in 2004. In 2005, the X-Trail FCV was updated with the first generation of Nissan's in-house FC stack technology. Variants of this model, including a 2008 update with a second-generation stack, were showcased across the world until late 2009. Nissan decided to focus its efforts on FC stack system development before showcasing new vehicles. Originally, Nissan planned to integrate this stack into a commercial FCEV from 2016 onwards. However, at the 2013 Tokyo Auto Show, Renault and Nissan pushed back their initial target to sell a combined M1.5 electric vehicles by 2017 by two to three years.[178]

Volkswagen is the third largest vehicle producer in the world. It produced M9.379 vehicles in 2013. Volkswagen's position to FCVs remains ambivalent. Though VW is a VES member, entered the CEP in 2006 and has also developed its own FCVs, it follows a multiple powertrain and fuel strategy. This strategy relied initially on next-generation engines, e.g. the

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[174] http://www.hyundainews.com/us/en-us/Media/PressRelease.aspx?mediaid=40852&title=hyundais-first-mass-produced-tucson-fuel-cell-cuvs-arrive-in-southern-california, 26.07.2014

[175] http://www.cnet.com/news/with-toyota-in-its-rear-view-mirror-gm-talks-fuel-cell-car-technology/; 08.08.2014

[176] http://gm-volt.com/2012/08/22/gm-hydrogen-fuel-cell-vehicle-update/; http://green.autoblog.com/2012/-10/10/gm-closes-ny-fuel-cell-facility-consolidates-hydrogen-research/; 22.01.2014

[177] http://www.cleanenergypartnership.de; 22.01.2013

[178] http://www.reuters.com/article/2013/11/20/us-autoshow-tokyo-nissan-idUSBRE9AJ0HU20131120, 26.12.2013; Fuel Cell Today, July 2013, p. 19

introduction of second generation biofuels such as SunFuel®, SunGas® and Bioethanol. Currently, VW is building the most efficient NGVs and is just introducing BEVs (Golf, up). VW has established a FCV and BEV Technology Centre in Isenbüttel. VW is evaluating the introduction of BEVs and FCV as a paradigm shift in the concept of individual mobility.[179]

The **automotive industry** is one of the most powerful industries of the world clearly capable of pushing the market entry of FCVs. The FCV-technology is ready for market release, see section 4.2.4, but market introduction would require heavy investment from industry in production facilities. The automotive industry has an excellent public relation machinery working and is steering a good part of the publications on alternative propulsion systems through the provision of technical information to the public via dedicated magazines, events, fairs (Detroit Motor Shown, Geneva Auto Show, IAA) etc. The car industry developed own FC stack system know-how (the main value creating component of the FCV) and keeps competitors such as FC system manufacturers at a distance. The specialised FC-companies are lacking the strength to market their developments without the automotive companies. Currently, the market strategies of the industry are diverse: the Asian companies Toyota, Honda and Hyunday are advocates for FCVs, Daimler is ambivalent between BEVs and FCVs, Nissan/Renault, PSA, BMW and VW are going for BEVs, GM/Opel have not revealed their stakes, Ford is quite strong at the US HEVs market, but recently reinforced its activities in the AFCC.

On the European agenda the German government and automotive industry, successfully lobbied for delaying the CO_2-standards from 2020 to 2021 and changing the rules of flexibility. They are trying to postpone a binding target for 2030 (the first target that probably would not be able to be fulfilled with conventional technology). Without a real necessity, the German automakers may not be ready to enter a new system approach. The industry needs to take care not to lose user acceptance for the conventional car and the belief in new BEV- and FCV-technology in Germany at the same time. For example, already as early as 1999 the IAA’s motto was “The car: meeting place for the future”; the IAA 2005 had a strong focus on hybrid and H_2-vehicles etc. Toyota is striving for FCV technology dominance. Jim Lentz, Toyota's CEO of North America, linked the company's push into FCVs to the development of the first Prius, a car that, with petrol costing at the time just over 1 USD/gallon, had little business justification.[180] The market shares of the German industry in the HEV market is comparable small, i.e. German car makers held 1.6% of the US HEV-market and 2.2% of the US PHEV-market, but 95.9% of the much smaller US diesel car market in 2013.[181] In Germany, the (P)HEV-market is also comparably small.

5.3.1.2 Fuel Cell Industry

The FC-industry is not a homogenous industry, but represents companies from a collection of different sectors. FC-applications are developing at different rates, with the full range currently spanning from experimental one-off prototypes to large projects relying heavily on government funding, right through to tens of thousands of small FC-units being already sold to the public, e.g. in 2014, Efoy advertised the sales of more than k20 systems since the year 2000[182]. Today, the advantages provided by specific types of FC often outweigh the performance of incumbent technologies. In particular, the portable and stationary FC-sector experienced good growth during recent years (see *Figure 5-6*).

179 http://www.cleanenergypartnership.de, 26.01.2013

180 http://www.autonews.com/article/20131125/OEM05/311259930#axzz2oJp4gsFE, 23.12.2013

181 In 2013 in the US k496 HEVs, k97 PHEVs and k138 diesel cars (less than 14,001 lb gross vehicle weight (6.351 kg)) were sold.http://www.hybridcars.com/december-2013-dashboard/; 03.08.2014

182 http://www.efoy-comfort.com/de/technische-daten; 04.08.2014

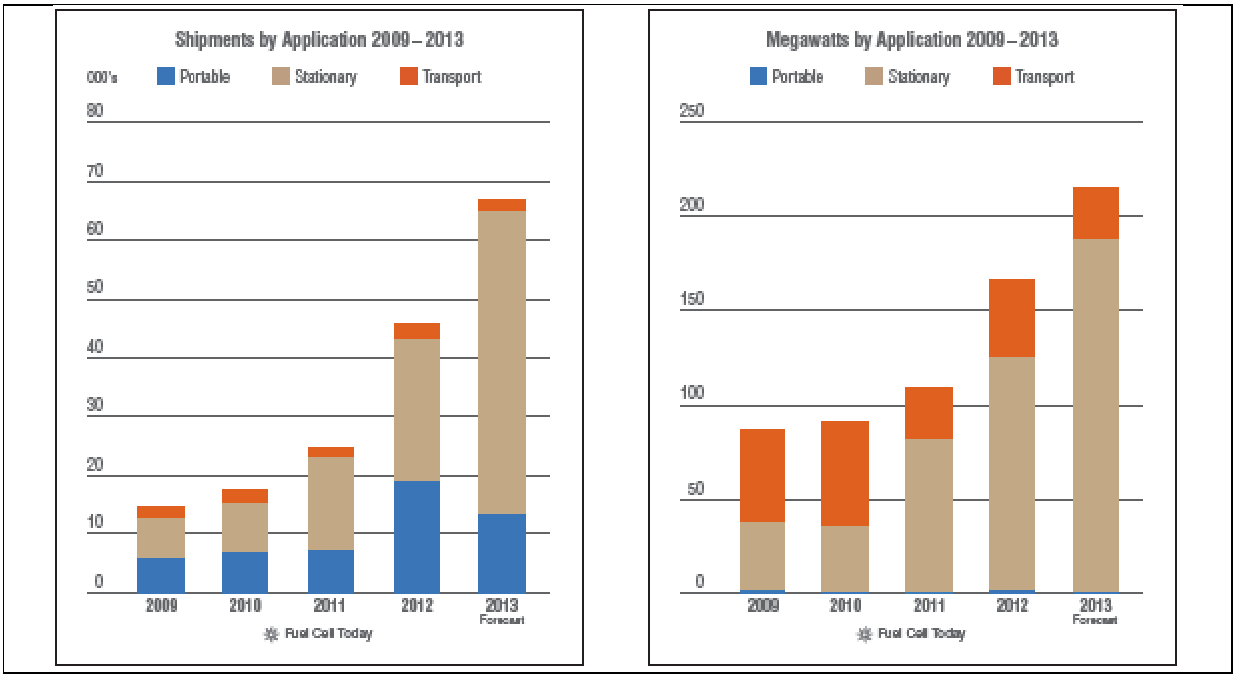

Figure 5-6: FC market development [FuelCell Today, 2013 (2), p. 6]

In the US, material handling became a large business for independent FC-manufacturers. In 2010, half of all transport sector shipments were for materials handling vehicles. In 2012 more than 2,770 FC-forklifts were in operation. [Curtin et.al., p. 3; FuelCell Today, 2013 (2), p. 13-15] FC-heating devices still need improvements in durability and service life, costs need to be reduced. However, during recent years the development was strongly targeted towards market introduction. [Badenhop, 2013, p. 146] The residential micro-CHP programme in Japan, known as EneFarm (including Tokyo gas, Panasonic, Toshiba, Eneos) targets to M1.4 units (200-750 W_e) by 2020. Introduction has been co-financed (e.g. k20 units in 2012 and k50 units in 2013). Financial contribution from the government is reduced each successive year and stops in 2015. PEMFC and SOFC are offered; currently the split is around 80% PEMFC and 20% SOFC.[183]

Thus, non-automotive applications seem to provide first market growth and profit potentials, also for PEMFC-producers. With a focus on 2015 as the commercialisation date for FCVs and the concurrent announcements regarding the introduction of infrastructure in Germany and the US, automotive FC technology suppliers also face growth opportunities. However, the large automotive manufacturers have developed their own FC-technology. In addition, most independent FC-producers still need to evolve from stack suppliers to energy system suppliers. This also includes the hybridisation of the FCV combining FCs with batteries or supercaps. Toward that end FC-manufacturers need to develop a deep understanding of the vehicle's overall requirements. Building close co-operations with Tier 1-suppliers[184] or OEMs is a crucial step. The entrants to the FC-market can be divided according to their background:

183 FuelCell Today 2013 (1); http://panasonic.co.jp/corp/news/official.data/data.dir/2013/10/en131021-5/en131021-5.html, 12.02.2014

184 "Tier 1" and "Tier 2"-suppliers are not official terms. In the automotive industry, they describe the relationship between the original equipment manufacturer (OEM) and its suppliers. The concept of "Tier" does not reflect the size or importance of a company; it mostly indicates who the end user of that company's product is. Basically, the OEMs are the name-brand car-makers like Daimler, Opel etc. A Tier 1 supplier is a company who produces for the OEMs i.e. companies like Delphi or Dana or Johnson Controls. Moving down the list, a Tier 2 supplier is somebody selling products to Delphi etc.

- Companies founded by an alliance of financially strong automotive companies to pool knowledge on the technology and to concentrate on research and development,
- Small start-up companies that focus on FC-technology; some are still independent, others have formed co-operations with technology suppliers or equipment producers,
- Companies founded by energy, electronics or other companies whose business is affected by the FC-technology.

Automotive Fuel Cell Cooperation: In 1998, Daimler-Benz AG, Stuttgart, Ford and Ballard Power Systems Inc., Vancouver signed an agreement on the so-called **Fuel Cell Alliance** with the goal to jointly develop an FC ready for series production. Until 2007, Ballard, Daimler and Ford invested over MUSD 700 in this alliance.[185] During the last 15 years several companies have been founded. For example **DBB Fuel Cell Engines GmbH** to develop FC-systems for automotive applications (renamed to '**XCELLSIS - The Fuel Cell Engine Company**' in 1999) and **Ecostar** to develop electric drive-train systems. Both were fully integrated to Ballard. [WSS 5/01, p. 3] In 2005 Daimler and Ford founded '**NuCellSys GmbH - The Fuel Cell System Company**' to develop and manufacture FCV-systems. Finally, in 2007, Daimler and Ford founded '**AFCC - Automotive Fuel Cell Cooperation**' which fully took over Ballard's automotive stack business.[186] AFCC expedited the development of FC-buses and cars with Ford and Daimler as the only customers. In the context of the crisis of the American car industry Ford had to reorganise and sold its share of NuCellSys to Daimler in 2009.[187] However, in 2013, Ford took over the 19.9% share from Ballard Systems. In 2013, the AFCC's owners signed an agreement with Nissan Motor Company to further develop FC-technology that shall lead to an affordable, mass-market FCEV by 2017.[188]

Ballard Power Systems, Canada was founded in 1979 to conduct R&D on high-energy Li-batteries. Ballard began developing FCs in 1983. The development of the company's stock exchange value decreased dramatically after the year 2000 when the market introduction of FCVs was postponed after 2010 (see *Figure 5-7*). From 2007 to 2009, Ballard shifted its strategic focus from long-term, high cost automotive FC R&D technology development, which was transferred to the AFCC, to FC-products for near-term commercial markets. This drives greater revenue and margin potential, whilst lowering risks. Products include backup power for wireless telecom networks, distributed power generation taking advantage of low-cost H_2-streams from chemical and biogas production, material handling and FC-buses. Ballard has designed and shipped close to 150 MW of H_2FC-technology to date.[189]

UTC Power, founded in 1958, is the only company with experience in all five major FC-technologies. UTC FCs have provided electric power and drinking water for astronauts on every manned space flight since the Apollo program, including the Space Shuttle missions. From the 1950s to the 1990s, UTC Power expanded its R&D to include FCs for buildings, marine and transport applications, in particular buses.[190] UTC Power was sold by UTC to **ClearEdge Power**, a US stationary FC producer in 2013. [WSS 02/2013, p. 2]

Doosan Corp., a South Korean conglomerate, bought ClearEdge Power Inc. for 32.4 MUSD in a bankruptcy auction in 2014. Also in 2014 Doosan agreed to buy Korea based FuelCell

185 http://www.daimler.com/Projects/c2c/channel/documents/1288614_Brennstoffzelle102007_e_lang.rtf, 15.11.2015
186 http://www.nucellsys.com/index.dhtml/2949576b3d3aa249672b/-/enEN/-/CS/-/Unternehmen/Geschichte, 28.12.2008
187 http://www.spiegel.de/auto/aktuell/0,1518,631990,00.html, 14.07.2009
188 http://www.afcc-auto.com/partners.php, 20.12.2013
189 http://www.ballard.com/about-ballard/, 15.03.2014
190 http://www.fuelcell.co.uk/utc-power/, 15.11.2015

Power Inc. Both companies have been integrated to **Doosan Fuel Cell America**. Doosan FC plans to extend the Connecticut-based operation.[191]

Figure 5-7: Development of Ballard Power System stock prices[192]

FuelCell Energy, Connecticut US**,** produces stationary MCFCs running on biogas, natural gas, coal gas and propane. The systems provide between 300 kW and 2.8 MW with an electric efficiency of 47%. In 2010, all stored materials and equipment of **MTU Onside Energy** were transferred to FuelCell Energy Solutions GmbH, the German daughter company of FuelCell Energy. FuelCell Energy is partnering **POSCO Power** in South Korea to market its MCFC technology for grid-connected power applications in Asia. Since 2008, POSCO constructed several MCFC-plant with an annual production capacity of 30-100 MW in South Korea. FCs are part of South Korea's national energy program as they can produce large amounts of electrical power in a relatively efficient manner. The country does not have the land that is needed to support large scale wind or solar projects. POSCO plans to provide 10 MW MCFCs for ships in 2016. [FuelCell Today, 2011, p. 10, 16] In 2014, FuelCell Energy entered into a strategic financing agreement with NRG Energy Inc. (one of the largest US energy suppliers) which purchased M14.6 shares (35 MUSD) claiming a 6% stake in the company.[193]

Figure 5-8: Development of FuelCell Energy stock prices[194]

191 http://www.clearedgepower.com/media/recentarticles/doosannumberone/; http://www.bloomberg.com/-news/2014-07-21/doosan-32-4-million-u-s-deal-marks-second-fuel-cell-buy.html; 06.08.2014

192 http://www.reuters.com/finance/stocks/chart?symbol=BLD.TO;13.04.2015

193 http://www.thestreet.com/story/12828288/1/why-fuelcell-energy-fcel-stock-is-climbing-today.html?-puc=CNNMONEY&cm_ven=CNNMONEY; 07.08.2014

194 http://www.reuters.com/finance/stocks/chart?symbol=FCEL.OQ, 13.04.2015

Hydrogenics, Canada has over 60 years of experience designing, manufacturing, building and installing industrial and commercial H_2-systems. This includes H_2-generators for industrial processes and fuelling stations, H_2FCs for urban buses, cars and lift trucks, FC-installations for freestanding electrical power plants and Uninterruptible Power Supply systems as well as H_2-storage and power systems for optimising solar and wind systems.[195]

Figure 5-9: Development of Hydrogenics Power System stock prices[196]

Nuvera, Italy was formed in 2000 through the merger of Epyx Corporation (expertise in fuel processor technology development) and De Nora Fuel Cells. It offers H_2-supply systems for multiple applications in the 25 to 250 kgH_2/d range. Nuvera has been supplying, so-called Orion PEMFCs (10-300 kW) to various vehicle manufacturers. Nuvera has experience in hybrid battery/FC powertrain development. **Proton Motor** is the only German manufacturer of H_2FC-systems for various applications, incl. automotive applications. Proton Motor has specialised in hybrid FCs and electrical energy storage systems. **H2Logic A/S**, Denmark manufactures FC-systems for material handling vehicles. It installed more than 10 H_2-stations with four stations during 2012. **Nedstack**, The Netherlands, manufactures PEMFCs in the 2-10 kW range. Depending on the application, the stacks are tailored for either high performance or extended lifetime.[197]

Toshiba is a diversified manufacturer and marketer of advanced electronic and electrical products, information and communications equipment, power systems, household appliances etc. **Toshiba Fuel Cell Power Systems Corporation** focuses on PEMFCs for the Japanese market. Among the main products are residential PEMFCs and 200 kW PAFCs, developed since the early 1990s in partnership with UTC Fuel Cells.[198]

Panasonic is a multinational electronics company headquartered in Japan. It offers household FC cogeneration systems. In 2009, it became the largest shareholder of **SANYO** which developed a one kW residential SOFC. Sanyo has research agreements with **Osaka Gas** on home CHPs, with **Hoku-Scientific** to develop MEAs for PEMFCs to power portable and home electric applications and with **Samsung** to jointly develop PEM-technology.

195 http://www.hydrogenics.com/about/; 15.03.2013
196 http://www.reuters.com/finance/stocks/chart?symbol=HYG.TO, 13.04.2015
197 http://www.nuvera.com, http://www.proton-motor.de, http://www.h2logic.com/, http://www.nedstack.com/products/nedstack-product-range, 08.08.2013
198 http://www.fuelcelleurope.org/index.php?m=3&sm=7&memberId=47, 10.09.2013

Panasonic and **Viessmann** agreed to launch FC-systems in Germany from 2014 onwards. By 2020 Panasonic and Viessmann expect a five digit number of systems to be installed.[199]

ACAL Energy, UK, a chemical company develops 10-100 kW stationary H_2PEMFC-systems. ACAL developed and patented a platinum free liquid catalyst, FlowCath®. Acal announced that this chemistry and engineering enabled an H_2PEMFC to reach k10 hours runtime, the equivalent of 0.5 Mkm driven, on a third party automotive industry durability test without any significant signs of degradation in 2013. [200] This durability is comparable to the best diesel LDV engines. Acal is funded by the UK Carbon Trust, I2BF Global Ventures, Solvay, a large Japanese automotive manufacturer and the North West Fund for Energy and Environment. Acal is backed by **Sumitomo**, a Japanese trading house.[201]

Currently, all automotive companies which announced FCV-introduction by 2017-2020 have developed own FC-stack technology. However, manufacturers who might decide to enter FCV-technology later may cooperate with an independent FC-producer to reduce own FC-technology development time. In particular Hydrogenics has large experience and does not have an automotive partner, yet.

5.3.1.3 Hydrogen technology

The global chemical gas companies are also producing hydrogen, thus they have a natural interest in expanding the H_2-fuel market.

Air Liquide, France, has been working along the H_2-production chain for over 40 years. The Group operates more than 200 H_2-production units, including 38 large capacity units. 95% of the hydrogen is produced from natural gas. These plants supply more than 1,800 km of H_2-pipelines in Europe (240 km in Germany), the United States and Asia. Air Liquide is a member of the CaFCP and the CEP. Air Liquide develops H_2-filling stations, e.g. in Düsseldorf.[202]

Air Products, Pennsylvania, is the world's largest supplier of merchant hydrogen. It commercially develops, supplies and operates turnkey H_2-plants. Air Products has over 50 years of H_2-experience. It deployed its first H_2-fuelling station in 1993 and owns many patents on LH_2- and GH_2-supply and dispensing technology, including systems for H_2-generation, purification and handling. Recent examples include supplying and fuelling H_2-buses in London and in Beijing for the Olympic Games. Air Products is a member of the CaFCP.[203]

Linde offers a wide range of technologies and (design) services related to CGH_2- and cryogenic LH_2-fuelling infrastructure. Its storage and transport facilities range from specially insulated tanks for LH_2 to pressure-tight containers (cylinders, cylinder bundles, tanks and pipes) for CGH_2. For road transport, Linde has dedicated CGH_2- and LH_2-trailers available. Linde transports large volumes of hydrogen over long distances via several pipeline networks.

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199 http://phys.org/news/2013-01-panasonic-trims-ene-farm-fuel-cell.html http://www.fuelcellmarkets.com/-fuel_cell_markets/industry/3,1,1,7,6907.html; http://content.yudu.com/A2q1Im/pssv4i2/resources/32.-htm; 27.07.2014

200 Over 16 months, ACAL Energy has put the FC through an industry standard automotive stress test protocol that simulates a 40-minute car journey with a start-stop at the end of each cycle. The cycle, which was repeated 24 hours a day, seven days a week, mimics a vehicle journey with frequent stops, starts and a highway cruise. This particular test is employed to accelerate aging and to stress wear on car engines and fuel cell systems over time. [http://www.acalenergy.co.uk/news/release/acal-energy-system-breaks-the-10000-hour-endurance-barrier/en, 04.08.2014]

201 http://www.acalenergy.co.uk/; http://www.bloomberg.com/news/2013-02-20/sumitomo-backed-acal-raises-funds-to-expand-fuel-cell-technology.html, 10.09.2013

202 http://airliquide.com, 23.01.2013

203 http://www.airproducts.com, 23.01.2013

Linde also constructs and integrates on-site facilities at fuelling stations to produce hydrogen locally (through reforming or electrolysis). Linde is operating a pilot plant to produce green hydrogen from raw glycerine, a by-product of biodiesel manufacture from plant oils such as rapeseed. In addition, Linde is operating an H_2-steam reforming plant, the largest industrial H_2-liquidification plant (capacity of 3 m³ LH_2/h) and an extended pipeline network in Leuna.[204]

Praxair Inc., Danbury, CT has been supplying hydrogen and application technologies for decades. For example, it offers modular on-site H_2-generation systems designed to produce 80-14,000 Nm³/h. [http://www.praxair.com, 26.01.2013]

Linde, AirLiquide and Air Products are participating in the German H_2-infrastructure development. AirLiquide is operating an H_2-station in Düsseldorf. However, it is not yet clear, if station operation could be a mid-term business model for AirLiquide. Also Air Products sees its role in H_2-supply. Both companies have the technology background and the financial ressources to enter H_2-supply and/or operation business. Linde has reduced its contribution to technoloy delivery during recent years.

The **wind-H_2 market** emerges with the erection of demonstration plants in Prenzlau (Enertrag), RH_2-WKA in Werder, Kessin, Altentreptow and Falkenhagen. These activities were accompanied by the foundation of the association “performing energy - Bündnis für Windwasserstoff (Alliance for wind hydrogen)”. The cost of wind-H_2 heavily depends on the regional circumstances, e.g. feasibility for direct feeding of H_2 to the gas network, availability of storage options (salt caverns) or of other users (power turbines, H_2-fuel market). Two studies investigated under which circumstances wind-H_2 could be used efficiently in Northern Germany or in the Lower Elbe region. [ChemCoast et. al., 2013; Stolzenburg 2013]

5.3.1.4 Other component suppliers

Most FCVs are hybrid systems. In consequence, FCV-manufacture also depends on the supply of energy storage systems, mainly batteries and other electro-technical technology, such as electric engines, components etc. The latter and basic battery technology are mature technologies, but there is a lack of advanced battery technology, operating experience for battery applications and energy management systems in vehicles. There are various other component producers with an interest that the market penetration of FCVs takes place. They have usually emerged from other branches, e.g. NGV-cylinder production and their influence on the market is quite small. Some examples are:

Dynetek, Canada, designed, developed and manufactured CGH_2-storage for transport and stationary applications in pressures ranging from 20 to 82.5 MPa. Dynetek provided 30 H_2-systems for the Citaro FC buses of the CUTE-project and supplied 25, 30 and 70 MPa cylinders to the VW Bora, Nissan Xterra, 2000 Mercedes Benz Necar, Ford Focus FCV, Toyota FCHV and the Ford H_2ICE vehicle. In 2012, the company was acquired by Luxfer, the world’s largest manufacturer of high-pressure aluminium and composite cylinders. The Dynetek’s H_2-type 3 cylinder technology is traded under its new name ‘Dynecell’.[205]

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204 http://www.linde-gas.com/en/innovations/hydrogen_energy/distribution_and_storage/index.html; http://financialreports.linde.com/2011/ar/lindeannual/growingpopularityofrenewableenergies/-greenhydrogenfromglycerine.html?cat=n; 23.01.2013

205 http://www.luxfercylinders.com/products/g-stor-alternative-fuel-cylinders/688-luxfer-dynecell; 05.08.2014

QUANTUM Technologies, Inc., Canada, has been designing and building H_2-refueling equipment since 2002. Quantum's original product line includes up to 70 MPa systems. Quantum currently operates eight H_2-refueling stations in the US.

Hexagon Lincoln, Norway, USA, has been supplying cylinders for H_2-applications since 2000. It was the first company to develop and offer 70 and 95 MPa tanks to the industry. Lincoln supplies a variety of major OEM's.[206]

5.3.2 Fuel supply sector

Many **electricity utilities** promote H_2-technology and have their own FC-programmes to support stationary FC-applications. Also the **majority of the oil companies** such as Shell, BP and Total are carrying on H_2-fuel programmes. Their motivation is ambivalent. On the one hand, some of the large mineral oil companies support the development of an H_2-infra-struture. On the other hand, Aral (part of BP) left the CEP in 2009. The company declared, that it has finalised learning on H_2-fuel with the conclusion that H_2-fuel from fossil sources is not sustainable and too expensive. However, BP remained a member of the CaFCP.

The **fuel retailers** face a difficult market environment; in consequence the number of filling stations was significantly reduced during recent years, see section 2.4. Traditional fuel retailers are losing market shares to non-traditional fuel retailers, including "big box stores", who often sell fuel with very low margins as a way of attracting customers to their stores. Fuel retailers are heavily relying on profits from their convenience stores, even if profit on fuel sales is still important. The retailers expect this trend to continue. The transitioning to the new H_2-technology is complex and expensive and the station owners must achieve a 3-5 year return on investment.

The retailers will play a leading role in the H_2-infrastructure development, therefore, their ambitions and commitments need to be carefully analysed before any conclusion on the market potential of H_2-vehicles can be made. The California Fuel Cell Partnership organised an online focus group of 14 large Californian fuel retailers to gauge their opinions and perspectives on alternative fuels and hydrogen. The results showed that adding hydrogen to the filling station has the advantage of acquiring some "green" customer segment, but the disadvantages are high upfront cost and low demand, resulting in unused capacity. The public relations value of "going green" has little impact and does not allow for more than a few "show dispensers". Today, the capital costs of a 700 kg/d H_2-station is too high to be covered by the retailer, see *Figure 4-9*.

Therefore, the **mineral oil industry** is currently investing in the H_2-stations, not the retailers, using heavy government support. In addition, the presumed additional regulations and liabilities for station owners could be prohibitive and some consumers may have a negative perception and low education levels about hydrogen. [IPHE, 2010, p. 3]

OMV, is one of the largest industrial Austrian companies (25.5 employees). It is supplying hydrogen to industrial customers and operates the H_2-stations in Vienna and Insbruck.[207]

Shell Hydrogen, Amsterdam, The Netherlands, opened several H_2-filling stations in partnership with car makers, e.g. in Tokyo, Reykjavik, Shanghai, Washington DC, New York, Los Angeles, Berlin and Hamburg. The main parent company Shell is a global group of energy and petrochemicals companies with around k90 employees in more than 80

[206] http://www.qtww.com/hydrogen-infrastructure, http://lincolncomposites.com, 25.07.2014

[207] http://www.omv.com/portal/01/com/omv/OMV_Group/About_OMV; 15.11.2015

countries. Shell operates the second-largest fuelling network in Germany, with more than k2 service stations. Shell has over 50 years experience in the production and use of hydrogen. Shell is a CEP-member, a member of the German H_2-Mobility initiative and has been a founding member of the Island ECTOS project.[208]

Total, France, is a global oil and gas company with operations in more than 130 countries. Total operates the fourth-largest fuelling network in Germany, with more than k1 service stations. Total has been promoting the use of hydrogen in transport since the millennium turn. Total opened its first H_2-filling station in Berlin in 2002 and is involved in several co-operations to develop and test H_2-technology, e.g. the CEP, HyFLEET:CUTE, the EC's FCH JTI and France's national H_2-action plan, PAN-H. Today, Total operates three H_2-filling stations in Berlin, one in Munich, one in Belgium and one in Hamburg. In 2012, Total built the world's first carbon-neutral fuel station at the future airport Berlin-Brandenburg, where a wind farm will supply energy for the carbon-free H_2-production. Total is also working on stationary applications, notably with Electrabel and Idratech.[209]

Participation in alternative fuel programmes could allow the mineral oil industry to comply with the legal requirements on fuel decarbonisation. The industry needs an alternative fuel which could be safely distributed with limited investments and risks. Biogas is one option, but the amount available is limited, see section 3.2.2. Furthermore, with decreasing oil resources, the mineral oil companies simply have to acquire new markets if they want to exist in 30 to 40 years. As technology development needs time, the mineral oil industry has to consider new tradable products today. Air Liquide, Linde, OMV, Shell and Total have joined H_2mobility to plan, erect and operate 400 H_2-stations in Germany, see section 4.1.3.

5.3.3 The public

The public shall be represented by the citizens, vehicle users and the government. It is clearly important for the industry to address the expectations of all three groups.

5.3.3.1 Citizens

The use of H_2FCVs promises several public benefits, see section 5.2, which affect all citizens directly, but supports also the targets of different levels of government (e.g. having the responsibility for managing local air quality) and the industry (e.g. being the main addressee of environmental regulations). H_2FCVs include also the use of public areas such as streets and parking places, but also the provision of mobility and (tax exemptions releasing from) a contribution to the budget. Furthermore, the use of H_2-fuel has more specific implications such as safety concerns in the case of a road accident or from neighbours of a filling station. Only recently, the H_2-filling station in Stuttgart had to be fully evacuated to prepare for the deactivation of an aerial bomb from the Second World War. The interest of the citizens is articulated in elections, through politics (see below), by respective NGOs and by individuals.

The German BUND (Bund Umwelt- und Naturschutz), together with other large German environmental organisations such as Greenpeace, Nabu and the VCD, claimed that the automotive industry regularly promised salvation from a new innovative technology to distract from the fact that it has not provided vehicles to fulfil the EU CO_2-regulations. The NGOs criticise that German car manufacturers once more receive several billions of Euro direct and

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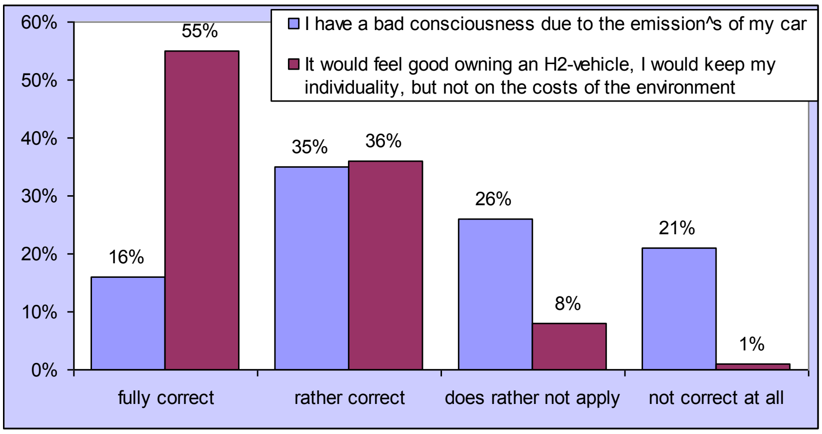
208 http://www.shell.com/global/environment-society/environment/climate-change/biofuels-alternative-energies-transport/hydrogen.html, 27.01.2013

209 http://www.total.com; http://www.cleanenergypartnership.de, 26.01.2013

indirect subsidies for the promotion of electric mobility by 2020. In the view of the NGOs this is a Potemkin village as long as the sale of high consumption vehicles is continued. They claim that the same had happened with FC-technology years ago. The BUND is asking for a revenue neutral programme to financially support the introduction of efficient vehicles on a technology neutral basis. The VCD introduces H_2FC-technology on its homepage as clean and efficient technology, but also criticises H_2-production as expensive and energy intensive. According to the VCD, it has a positive climate effect only if green energy is used. VCD also complains that the timing for the market introduction of the technology is unclear.[210]

In the absence of normal FCV-users the H_2-Trust[211] project organised a conference involving Berlin-Brandenburg citizens to discuss H_2FCV-technology. The interested citizens required more information to the public on environmental benefits, safety, handling and costs of FCV-technology. Information should not be solely provided by the automotive and energy industry for a better acceptance of H_2-technology. The poll emphasised that H_2-fuel would allow people to stay with the advantages of the incumbent car, but to drive environmentally-friendly. They would not need to change their behaviour to have a good conscience when driving. The majority of the polled citizens stated that they were ready to buy an H_2-fuel propelled car as long as it is proven from independent sources that this is a good alternative (see *Figure 5-10*). Those polled also stated that hydrogen has to be produced from renewable resources to gain social acceptance. The polled citizens recognised the necessity for a change in mobility. They requested from the government to set the political framework conditions for an environmental friendly and socially acceptable mobility.



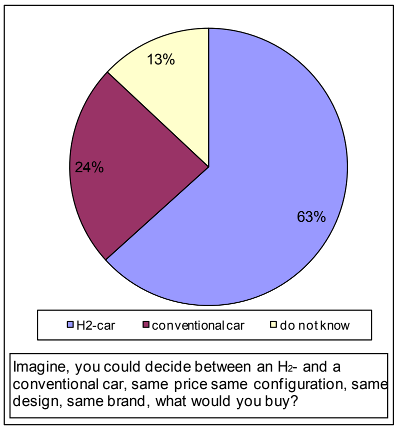


Figure 5-10: Questioning of citizens about car usage (left) and buying decision (right) [Welke, 2012, p. 10-16]

5.3.3.2 FCV-users and the consumer-adoption-process

The position of the user is quite unclear as there are currently only a small number of 'standard' FCV-users, for example at bus companies. In the framework of the CEP some vehicles have been leased to commercial users such as Deutsche Telekom, Hermes, BSR and BVG. These drivers already have experience with the technology in daily life. NOW and others have funded studies on user and citizen acceptance of H_2FC-technology. **Acceptance** shall be read as a positive attitude of larger groups of the society towards a certain tech-

210 http://www.bund.net/nc/presse/pressemitteilungen/detail/zurueck/pressemitteilungen/artikel/mit-dem-elektromobil-durch-potemkinsche-doerfer-umweltschutzverbaende-fordern-realitaetscheck-fuer/, http://www.vcd.org, 30.01.2013

211 H_2Trust is an EU funded project with the target to ensure that non-technical barriers to the deployment of H_2 and FC technologies are properly addressed.

nology which is directly articulated or indirectly shown by behaviour at a defined moment in time. [Dinse, 2001, p.23, 26]

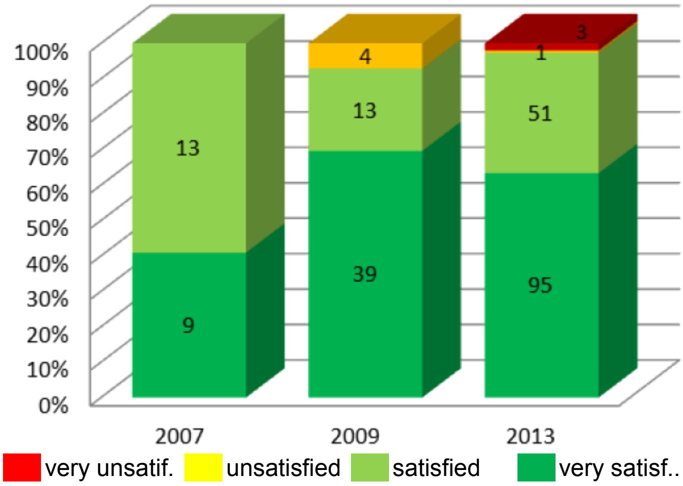


Figure 5-11: Driver acceptance of FCVs [Herbert, 2013, p. 15-19]

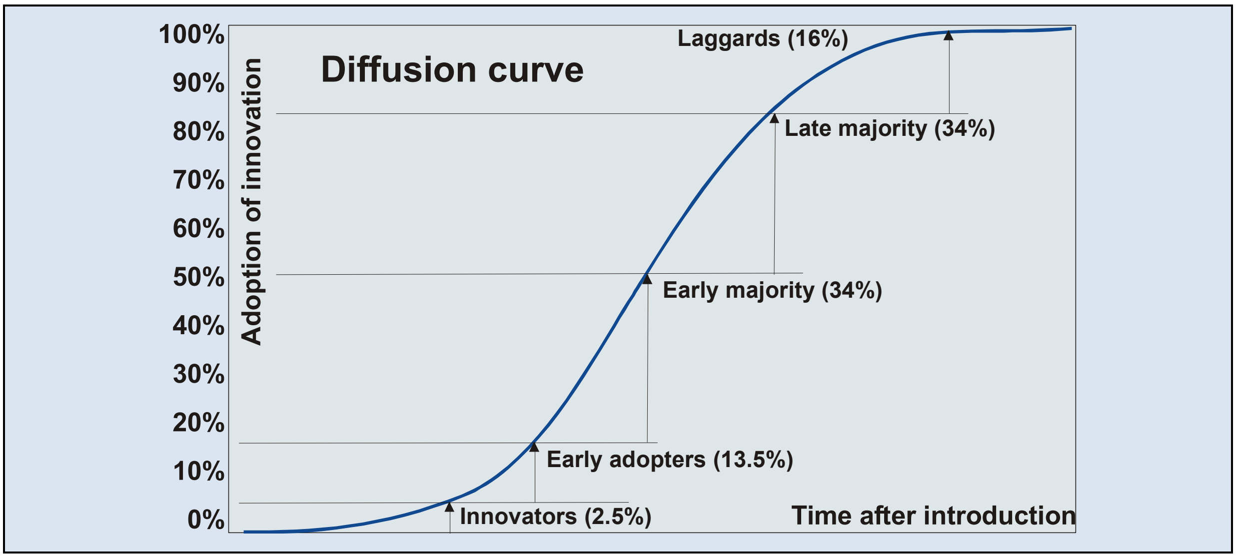
Within the CEP-project drivers of 169 FC-B-class (64%), Opel Hydrogen 4 (22%) and other FCVs were questioned. The level of satisfaction with H_2FCV-technology increased with maturity of the technology over time even if more and more drivers with no professional relation to the technology have gained access to the FCVs. During the first test years in particular the low temperature range of the FCV was annoying. At minus temperatures the FCV could only be parked outside for a limited time. In 2013, dissatisfaction with the technology mainly arose from the filling process, i.e. the respondents very often (9%) or often (34%) reported problems in starting the filling process or interruptions during filling. By comparison, only 13% of the respondents reported regular failure of the FCVs. Only 19% of the respondents would not recommend FCVs to friends, mainly due to the lack of and unreliability of filling stations as well as the high price of FCVs.

The level of user acceptance is not a static term, but is changing in the course of time. It is influenced by the progress of the H_2FC-technology itself, by the direction of the public discourse on H_2FCV- or other alternative propulsion technologies as well as by external events such as the Fukushima catastrophe or a turnaround in the energy politics. The consumer-adoption-process describes how customers learn about new-products, try them and adopt or reject them. **Adoption** is an individual's decision to become a regular user of a product. The consumer-adoption-process for innovative technologies is normally not a mass-market approach, i.e. launching the product everywhere and advertising it to everyone is not suitable, because not everyone is a potential buyer of the technology. The better approach is to draw on a dedicated marketing strategy, where the product is initially aimed at suitable users such as fleet operators, frequent or wealthy "green" drivers etc. However, also these consumers differ in their interest in new products and brands or are very loyal to their existing brands. For example, the current Daimler B-Cell is only available with light cream-coloured leather seats. This elegant look may be attractive to individual drivers, but is not suitable for fleet vehicles used by various drivers. Thus, beyond all innovation, the product needs to also fit the daily, simpler needs of the targeted user.

H_2FCV-technology marketing has to aim at those consumers who are **early adopters** to be successful. Early adopters are adventurous and enjoy the risk of being at the forefront. They prefer to test new technologies shortly after their first exposure on the market. Efficient media has to exist to reach these early adopters. Early adopters are opinion leaders and are very helpful in advertising the new product to other potential buyers. According to the theory, early adopters and innovators make up around 16% of *potential users* (see *Figure 5-12*).

Beyond the early adopters users are risk averse and more pragmatic. H_2FCV-technology must have an added value such as lower TCO; being new is no longer enough. In the midterm it will be necessary to change the marketing strategy to reach this 'majority' user group. The consumer-adoption-process focuses on the mental process through which an individual passes from first hearing, i.e. awareness about an innovation to interest, evaluation, trial and final adoption. Marketing of new products needs to focus on pushing consumer movement through these stages. [Kotler, 1997, p. 335-336]

The risk for H_2FCV-technology to stick in the interest stage is high because, due to high investment costs for a vehicle, consumers may not buy. This becomes obvious in the marketing process of BEVs: the consumer is not ready to pay an extra of 10-15 k€ for the batteries. Currently, the industry is introducing two new technologies to the market, i.e. BEVs and FCVs, requesting large investments for technology development and marketing (incl. infrastructure) for both systems. At the moment it looks as if the manufacturers may be divided into two 'camps': the supporters of FCVs and the advocates of BEVs, see section 6.1. The technology which manages to gather supporters from other industries to share risks and costs would have an advantage. The electricity industry, the main industry related to BEVs, could be a supporter of both BEVs and FCVs. However, the electricity industry has to manage the challenges of the 'Energiewende' and is probably not willing, or is not in a position, to contribute to the infrastructure development for innovative car concepts.



Adopter type	Characteristic	Role and size
Innovators Enthusiasts	Adventurous; Enjoy the risk of being on the cutting edge; Demand technology.	Market drivers. Want more technology, better performance. (16%)
Early adopters Visionaries	Well connected; Integrated in the main-stream of social system; Project oriented; Risk takers; Willing to experiment; Self-sufficient.	
THE CHASM (where marketing and distribution must radically change)		
Early majority Pragmatists	Deliberate; Process oriented; Risk Averse; Want proven applications; May need significant support; Vertically connected and act as their superiors.	Followers on the market. Want solution and conve-nience. (50%)
Late majority Conservatives	Sceptical; Does not like change in general. Changes under 'pressure' from the majority.	(84%)
Laggards Sceptics	Traditional; Point of reference is 'the good old days'; Actively resist innovations.	Interests different from status quo. (100%)

Figure 5-12: Customer groups according to time of market entry [IEA/OECD 2003, p.108]

The characteristic of the innovation affects its rate of adoption. [Kotler, 1997, p. 337] The greater the **perceived relative advantage of H_2FCV-technology** is, the more quickly it will be adopted. The consumer acceptance studies show, that the **technologies' advantages**

are highly communicable. H_2FC-technology offers clean, individual mobility very close to the comfort level of today's car. Advanced transport technologies are highly compatible with the high environmental consciousness of Western societies. The German automotive industry has a self-understanding of being an innovator testing advanced technologies on German highways. Thus, values fit. The implementation of NGVs has paved the ground for user acceptance of gaseous fuels. Nevertheless, H_2FCV-technology is weighed down by high FCV-costs, a low filling station density and uncertainty of the life-time of components. Moreover, users have different demands and some users may value the on-board access to large amounts of electricity more highly than the reduced mileage of FCVs.

The **H_2FC-technology's divisibility**, i.e. degree to which the technology can be tried, is limited today. This could be changed through the wide availability of FCV rental or sharing. For comparison, BEVs are already used as car sharing vehicles, allowing users to test the technology without the need to buy and to share risks. Leasing of FCVs to users has just started. **H_2FCV-technology compatibility**, i.e. the degree to which it matches the expectations of individuals has reached a good level to date. **H_2FCV-technology complexity**, i.e. the degree to which it is difficult to understand or use is quite low. Only the user's filling behaviour has to change. Due to the low density of filling stations, the onus is on the driver to keep an eye on the remaining fuel level. FCV-drivers would need to better plan fuelling or to explore alternative transport options, in particular for longer trips. Thus, in conclusion, the characteristics of FCVs, cleverly marketed, should not prove an essential market barrier, but should be a driver for market introduction.

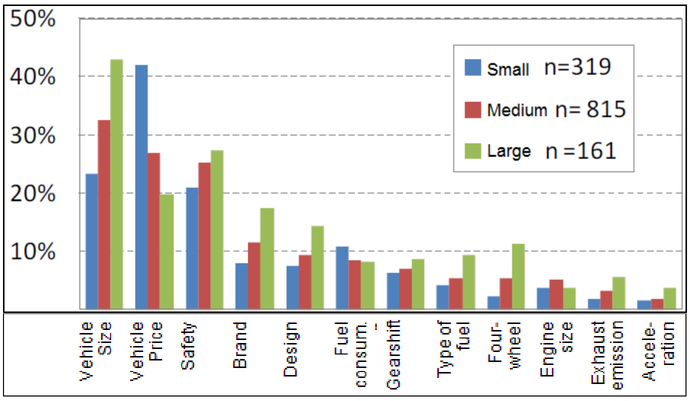


Figure 5-13: Decision factors for purchasing vehicles of various size [Plötz, 2013, p. 5]

The VECTOR 21 study simulates competition between propulsion concepts. The model differentiates 900 user types according to annual mileage, readiness-to-pay (early adopters are ready to pay a 10% premium) and preferred vehicle size. The model includes all propulsion types currently available. Specific TCOs are calculated on the basis of investment costs, taxes and fuel costs (linked to the annual mileage). The model selects a vehicle class suitable for each user type and excludes propulsion systems which do not comply with infrastructure needs or readiness-to-pay. In the final step, it is assumed that the user would decide to purchase the vehicle with the lowest CO_2-emissions. Even if these selection criteria must be critically questioned[212], this scenario shows interesting results. The CO_2-fleet regulation, oil price, tax incentives for the use of CNG and the availability of an H_2-infrastructure are variables in the scenario. In the basic scenario the CO_2-fleet limit decreases to 70 gCO_2/km in 2030 and to 45 gCO_2/km in 2040. This would result in the annual registration of k50 FCVs by 2030 and k60 FCVs by 2040 (2% registration share). If the H_2-infrastructure is excluded as a restricting factor (a fuel price of 5.95 €/kgH_2 (w/o taxes) and a carbon intensity of 9 gCO_2/km (for H_2FCVs) are

212 Fraunhofer ISI surveyed 1,295 purchasers for an analysis of the factors influencing new vehicle purchase decisions (see *Figure 5-13*). Buyers of large vehicles value the size and safety of the vehicle as the main decision factor. The vehicle price and brand rank only 3rd and 4th. Design and the availability of a four-wheel drive are also important buying decisions. Buyers of small vehicles rank price first, followed by size, safety and fuel consumption. Buyers of medium-sized vehicles rank in order of size, price, safety and brand.

assumed in 2040), there are M2.3 more FCVs registered by 2040 than in the basis scenario (about M0.22 FCVs (7.1%) are newly registered in 2040 p.a.). This result shows the significance of the H_2-infrastrucure as a market barrier. If the CO_2-fleet limit is kept at 95 gCO_2/km, there is no FCV registration in 2040. [Brokate et.al., 2013, 13-15, 25-26]

5.3.3.3 The role of government

In particular, when dealing with the interests of the public stakeholders, the multi-dimensional characteristic of "stake" becomes obvious. It is not solely measured in monetary-terms, but integrates aspects of voting power, economic power and political power. [Freeman, p. 59-61] The politicians offer their programmes and work in return for the benefits associated with a political office, e.g. power, prestige, income, feeling of contributing to the good of the nation etc. [Kirsch, 2004, p. 256-257] In an indirect democracy, citizens and politicians are interlinked in a principal-agent-relationship. The principle is the citizen, who poses the right to make certain decisions to the agent, i.e. the politicians, which have the power to legislate. The agent shall decide not only in the name of and for the account of the citizen, but he needs to deliver in accordance with the needs and preferences of the citizen or consumer to be elected again. Simply put, the party which offers the programme which best fits to the needs of the public is elected forming the government.

The government and its executing organisations are meant to represent the interests of the citizens, however politicians and bureaucrats are also driven by own interests. In reality, the content of the governmental funding programme is normally a compromise of several trends between the respective party and society. Furthermore, the politician individual does not normally hold the professional qualification for evaluating details and consequences of any particular technology and innovation policy; this makes it easier to find these compromises. Technical and scientific input for the political programmes is delivered by the Office of Technology Assessment, an independent scientific institution aimed at advising the German Bundestag and its committees, dedicated studies from various scientific institutes, lobbying and working groups etc. (see section 4.1 for exemplary studies).[213] Political programmes tend to be targeted to reach a wide consensus, rather than producing the best solution. Thus, the results may not be always rational, but are widely accepted:

- "Large" and new solutions signalling energy or problem solving capacity and allow for a high advertisement effect (key words: lighthouse and shop window projects) may be favoured against measures which only optimise existing solutions e.g. improvement of combustion properties or efficiency of conventional fuels.
- In the past, the size of the projects funded increased in terms of (multi-national) partners and financial volume. It would be probably difficult to build enhancements projects for incumbent technology, because partners would need to provide too much knowledge on technology and strategy. Furthermore, funding of technology which is close to the market may be interpreted as granting of a direct subsidy to companies involved.
- Decisions highly depend on input data, i.e. the industrial beneficiaries of the programmes provide the main input data which puts them into position to select data.
- Lobbying and safeguarding of interests of specific groups of electors lead to compromises not related to the target of the respective support programmes. Industrial and research representatives present their project ideas to politicians and to the public to improve their chances of funding. The most convincing concepts may be included in the programmes.

213 http://www.tab-beim-bundestag.de/en/about-tab/client.html, 21.12.2013

In this context, good rhetorical capabilities may partly replace technological feasibility and societal urgency.

- Competition between nations leads to amplifying effects: H_2FC-technology research achieved major importance in the R&D policies and priorities of the leading world economies and intergovernmental bodies like the International Energy Agency. The respective governments have staffed considerable funding programmes to promote H_2FC-technology and to support their local industry in achieving a leading position on the world market, e.g. the European FPs, the US Hydrogen Fuel Initiative and FreedomCar programmes, the Japanese New Hydrogen Project, the German H_2FC Technology Innovation Programme, the Chinese Green Olympic Protocol etc.

The research departments of companies, universities and similar institutions are the place of origin of technology innovation, the government works as a stimulator by setting an innovation-friendly regulatory framework or by implementing fiscal or other subsidising measures. In general, governments are concentrating on environmental and climate targets as well as on energy and industrial policy when acting on alternative fuels, section 3.1. These targets may be conflicting, e.g. environmental protection would require more regulation which could hinder industrial policy. A clean fuels policy promises an improvement in image for the government. In addition, clean, lean and safe cars are not only societal desirable, but also have the potential to create a competitive advantage of the European car industry, if they meet the consumer's expectations and are affordable. Consulting with stakeholders, Impact Assessment of policy measures and Guidelines on distributing funds shall ensure a high level of compliance with all stakeholders' interests.

The support by local, national and international policy will play a crucial role in overcoming the most pressing H_2-fuel marketing barriers, see section 5.1. In any case, not all governmental bodies may act in line with the political targets set by Parliament. Decision-makers in administrations may follow other targets. For example, the German Environmental Agency UBA qualifies hydrogen of being only a long-term solution beyond 2050.[214] At the same moment, the German government supports the development of an H_2-fuel infrastructure to support the market introduction of FCVs from 2017 onwards. [BMVBS, 2013, p. 28]

5.3.4 Classification of stakeholders

Stakeholders may be distinguished according to their power to affect the market introduction of H_2-fuel and their interest in it. It may be direct power, e.g. over budgets, legislative power or indirect power, e.g. ability to coerce or persuade others. The power a stakeholder holds may depend on formal hierarchy, authority of leadership, legislative power, control of strategic resources, possession of specialist knowledge, ability to mobilise people (lobbying, public awareness raising) and/or negotiating position in relation to other stakeholders. The knowledge on power sources allows to address the various interests in a dedicated way. A power-interest grid, developed by Eden and Ackermann, 1998 has been chosen to determine and depict the players' interests and power bases concerning H_2FCV-technology (see *Figure 5-14*). It is well suited to verify the stakeholders' statements on the strength of their stake towards hydrogen and to reveal real interests. In addition, it shows the way to convince low-interest stakeholders to change their views and could guide the authorities to give instructions, even with the threat of sanctions or punishment. The power-interest-grid

[214] http://www.umweltbundesamt.de/themen/verkehr-laerm/kraft-betriebsstoffe/alternative-kraftstoffe, 25.12.2013

highlights which coalitions may be worth being supported. The four stakeholder groups of the H_2FC-technology power-interest grid are:

- **Players**: They have a great interest in the market introduction of H_2-fuel and the power, i.e. funds and influence, to promote the market penetration process. Players are the *chemical gas and the mineral oil industry as well as the specialist H_2-equipment producers*. In addition, by spending many funds on dedicated projects and setting the legislative framework, the *government* put itself in the category of players. Only recently the EC suggested a Directive supporting the H_2-infrastructure [EC, COM(2013)18 final].
- **Subjects**: They have a large interest in the market introduction of H_2-fuel, but lack the power to influence the market penetration process. Subjects constitute a risk, because their mid-term existence in the market is often unclear. Subjects are, in many cases, young, innovative, growing companies, with a high interest in the market growth, but low power, i.e. financial means (liquidity, investment capital etc.). Subjects of H_2-fuel are dedicated, highly qualified component suppliers which are necessary for the development of good advanced technologies, but they will not have the means to go through a long market penetration process. They will either be integrated into the production line of one of the large industrial players or they depend on a growing market to refinance R&D costs. Typical subjects are battery, FC, onboard storage container and other *component manufacturers*. However, *users* are also subjects, because even if the users would prefer to use clean vehicles, they do not have the power to initiate the market penetration of FCVs. In any case, their position may change during the market penetration process to the player's role, because when vehicles and infrastructure are available, users will significantly determine the velocity of market penetration. In the end, they have to become the main investors in the technology for a successful market penetration.
- **Context setters** have power over the market introduction process of H_2-fuel, but no direct high interest. They cause a significant risk to the progress and implementation of H_2-fuel. The *automotive industry* is a context setter. They would have the power (financial, lobbying, e.g. for or against regulation and media influence) to implement FCVs, but are hesitating to market vehicles due to the related risks and the high costs. Anyhow, their interest in FCVs is limited as long as the sale of incumbent technologies is profitable and possible. Implementation of FCVs will displace incumbent technologies, leaving behind stranded investments, markets will be newly sorted, new players will evolve: this may threaten the current position of the automotive industry or individual companies, which are not properly prepared for H_2FCV-technology.

  Environmental NGOs make another group of context setters. They do not have direct power, but they have the capability to heavily influence public and political opinion on alternative technologies. Naturally, NGOs have no direct interest in a particular technology, but in the consequences of their use to health, environment, nature etc.
- **The masses**: crowds have little interest in the market introduction of H_2-fuel and little power to influence. The general public will have few possibilities to influence the market introduction process of H_2-fuel. In addition, "the-man-in-the-street" also has few interests in the market introduction of an alternative fuel or propulsion technology if he is not directly concerned, e.g. as a neighbour of a filling station.

The role of the stakeholders is not static; stakeholders are in a relationship with one another and influence each other. For example, the introduction of penalties for not meeting the EU CO_2-fleet standard increases the interest of vehicle manufacturers in low-carbon propulsion systems. The manufacturers will advocate the technology which appears the most profitable – in terms of direct profit as well as market and technology leadership – in the short-to-mid-term. Thus, in particular, the manufacturers of large, heavy premium vehicles may come to the conclusion that the use of clean FC-technology will be cheaper – again in direct money terms as well as prospects, image and prestige – than the continuation with advanced, but still incumbent, combustion engine technology.

	Low power	High power
High interest	**Subjects:** have a significant interest, but little power - Fuel Cell Industry - Battery component suppliers - Other component suppliers - Users	**Players:** have a significant interest and substantial power - Hydrogen technology manufacturers - Chemical gas and mineral oil industry - Government - (Users)
Low interest	**Crowd:** have little interest and not much power - Citizens	**Context setters:** have substantial power, but little direct interest - Automotive industry - NGOs

Figure 5-14: Power versus interest grid [adapted from: Bryson, J. M., 2004, p. 30-31]

However, in the end success and velocity of market introduction will depend on the push of the government, because the gas industry may install the H_2-infrastructure, but it lacks the means to supply FCVs. The car manufacturers will need regulatory pressure to enter this new technology. Financial incentives will not be sufficient, because the costs for R&D, components etc. are too high. Only regulation will have the power to push H_2FCV-technology through the market introduction process. It is able to provide a reliable framework essential for the industry to invest in large scale production facilities and to finally achieve the cost targets necessary for a self-perpetuating market growth, through continued R&D and economy of scales. However, the buying public also expects from the government the provision of reliable, affordable and clean, individual car transport options. The user's direct readiness to pay is limited, see section 6.3.2.4. A conflict may arise between the two expectations, if costs of transport increase significantly. Finally, governments depend on the support of the voters to set clean fuel regulation. This means that regulation has to be well apportioned so as not to increase the Total Cost of Ownership of cars too much.

5.4 Life-Cycle approaches, experience curves and technology learning

Most new technologies follow a similar life-cycle describing the technological maturity of a product. It applies to an entire technology or a technology generation. For example, H_2-transport technology as a product exists as one transport solution among many others such as incumbent vehicle technology or public transport to meet the need of mobility. The **product-life-cycle** portrays the sales of a product that have managed to reach market penetration, see *Figure 5-15*. The product-life-cycle ideally follows a bell-shaped curve. This curve is typically divided into four stages and shows different opportunities for attaining a profit depending on the level of sales.

The *introduction of products to the market* is a period of slow sales growth. It involves heavy expenses, thus no profit can be obtained. The number of sales is low, if there are any relevant sales numbers at all. For advanced technology products the introduction phase can be further divided into the development, i.e. R&D-, the technology deployment and the market introduction phase. All three phases overlap and affect one another. For highly

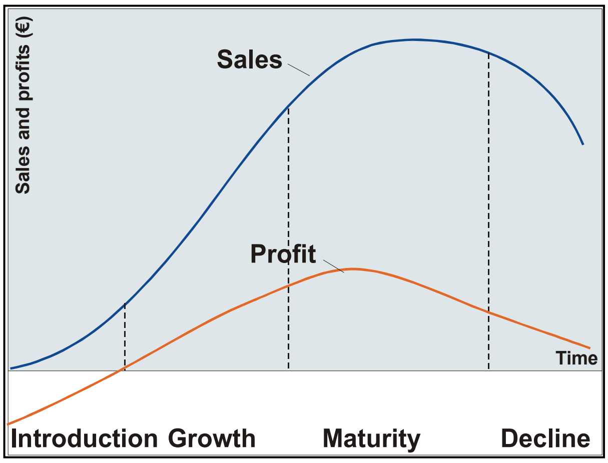
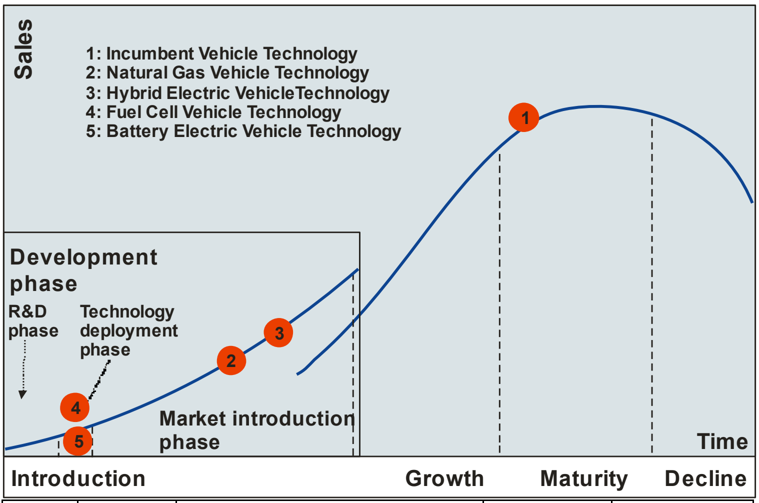


Figure 5-15: Sales and profits in a product life cycle [Kotler 1997, p. 346]

innovative products the development time is longer and the development costs are higher than for routine products. The introduction phase offers crucial learning chances. The two-way feedback between market experience and research is especially important for technology improvement and cost reduction. [Kotler, 1997, p. 346, Goldmann et.al. 1982, In: Kotler, p. 348] In the US, vehicle technology in general left the introduction phase before World War II when Henry Ford successfully implemented his T-model in the market.

Figure 5-16 suggests the position of some propulsion technologies within the Product-Life-Concept from a German market viewpoint as market penetration strongly depends on the local circumstances. National markets vary strongly in the quantity and quality of vehicles on the road (share of alternative vehicles, size of vehicles, etc.), the number of filling stations available and technology used (conversion kits or OEMs) etc. The evaluation uses the practical value of the various technologies from a German user's point of view. The practical value includes the multitude of models available on the market, level of limitation in daily use and acceptance of users measured in new registration figures. Today, various advanced vehicle technologies are in the market introduction phase, such as FCVs or BEVs.



	N° of models	Limitations	Registr. 2013	Vehicles in use 1/2014
NGV	Few	Filling station density	7,835	79,065
HEV	>10	None	26,348	85,575
FCV	>5	Infrastructure, costs	Few	85
BEV	>5	Mileage (winter!), costs infrastruct., battery durab.	6,051	12,156

Figure 5-16: Schematic classification of propulsion systems to the product-life cycle[215]

Within this thesis, FCVs are set at the same level as BEVs even if there are not so many models available yet, but manufacturers have signalled a market introduction by 2015-2017. However, FCV-technology has, from a user's point of view, a larger practical value and therefore the chance to outdistance BEV numbers in use quickly, see section 6.4.2. Furthermore, standardisation of FCVs is far ahead of BEVs; another indicator for the technology development level. This is in particular true for the standardisation of the infrastructure. In Germany, a concept for H_2-infrastructure implementation is available and the first filling stations have been erected in a coordinated way, including a German-wide operating billing system. The erection of battery charge points is in the hands of local companies and even the municipal energy companies have not yet managed to agree on a joint invoicing or card system. With a growing mileage of BEVs this obstacle will become a

[215] Own depiction, data from Kraftfahrtbundesamt

topic. However, BMW, Daimler and VW recently released attractive BEVs (BMW i3, VW e-up, e-Golf etc.).

HEVs and NGVs are in the market introduction phase. The number of HEV models available and the sales figures are increasing. Registration figures are roughly three times the amount of NGV registrations and the number of HEVs in use outnumbers that of NGVs since the end of 2013. The hybridisation share of the new car registrations is continuously growing and reached 0.9% in 2013. NGVs have been available on the market since the 1990s. Recently the sales figures slightly increased again after the strong promotion of biogas and the introduction of some very efficient new models (VWup, VW Passat etc.). Based on TCOs NGVs are very competitive, but have not managed to gain a wide acceptance, both of dealers and users, even after years of marketing. [Plötz, 2013, p. 7] The announcement to possibly prolong the tax exemption beyond 2018 may have the potential to push NGVs finally to the growth phase. By contrast, the registration figures continue to stagnate at a level not large enough to use the capacity of the NGV-filling stations efficiently. In this case, the technology implementation remains at a low level in a subsidised, uncertain future-something status.

The *growth phase* is a period of rapid market acceptance and an (at least theoretically) exponential sales growth combined with a substantial profit improvement. The length of the market introduction and early growth phase of FCV-technology and H_2-fuel will be heavily intertwined with the availability of an H_2-infrastructure, new distribution channels, services and communications. Also the car dealers need to readily accept and promote the new product. Naturally, the consumers need to have an interest in the product, adopt it early and give it favourable word of mouth.

Today, the conventional car is a *mature* product with a market share of more than 98% in a more or less stagnating German and European market, i.e. sales growth is slowed down and the product has achieved acceptance with most potential buyers, but there is still development potential (efficiency, safety). However, in contrast to theory, the profits of the automotive industry have not stabilised or declined. The Western European vehicle market is mainly a replacement market. With the population decreasing slowly between 2000 and 2030, this status will be probably kept. This in turn implies that the rate at which European consumers renew their vehicles is a key performance factor of the market. The holding period of cars has significantly shortened in Germany between 2006 (8.6 years) and 2012 (5.6 years (puls)/ 7 years (mobile)).[216]

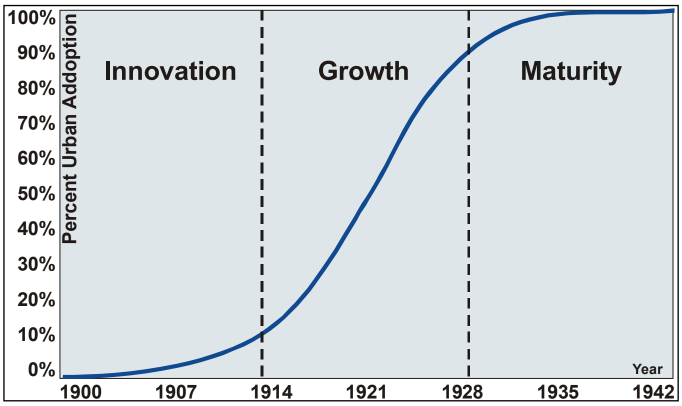


Figure 5-17: Product innovation cycle, S-curve on technology market penetration [Dent, 1994, p. 109]

The *market decline phase* is characterised by a downward drift of the sales and eroding profits. A decline phase is not visible for the product car, yet. [Kotler, 1997, p. 346]

In summary, the maturity phase of the conventional car is already lasting a long time because consumer taste and product technology are fairly stable. In this stagnating market, H_2FCV-technology has to edge out the incumbent technology in a predatory competition.

216 puls Marktforschung: http://www.gw-trends.de/umfrage-haltedauer-sinkt-auf-5-6-jahre-1144199.html; http://advertising.mobile.de/sites/default/files/120215_PI_Umfrage_Autowechsel.pdf; 31.01.2012

The **Product Innovation Cycle** of innovation, growth and maturity can be used to build a structured view of consumer attitudes that is helpful in developing market strategies and in understanding deployment policies. [IEA/OECD, 2003, p. 106] In the ideal case all three market penetration phases have the same duration forming an S-curve, i.e. it takes the same time for a new technology or product to go from 10% (end of the innovation phase) to 90% of adoption (end of the growth phase) as it does from 90% to 100% (maturity phase). *Figure 5-17* depicts an idealised S-curve for the market penetration of the early automobile in the US. In 1900 very few people possessed automobiles. Between 1900 and 1914, the automobile went through its innovation phase; at the end of it Henry Ford introduced the assembly line. Subsequently automobiles became affordable for the middle class and they moved into the mainstream. Between 1914 and 1928 the automobile went through its growth phase, during which the market potential increased from 10% to 90% of urban US families. The S-curve is only sometimes very smooth, but is equally often irregular, asymmetric or sporadic, (see *Figure 5-18*).

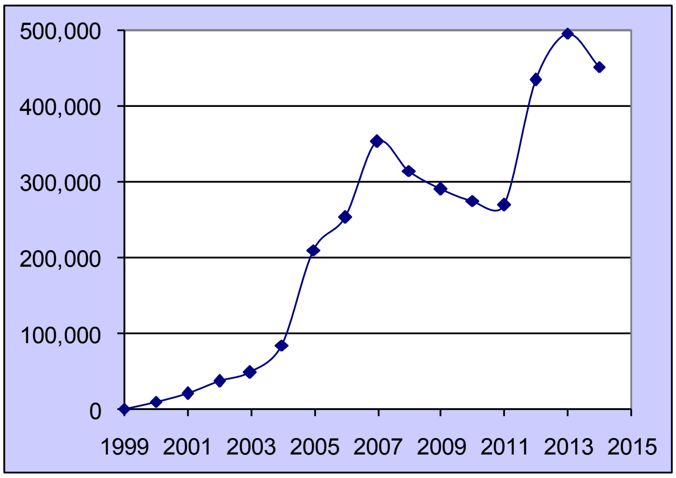


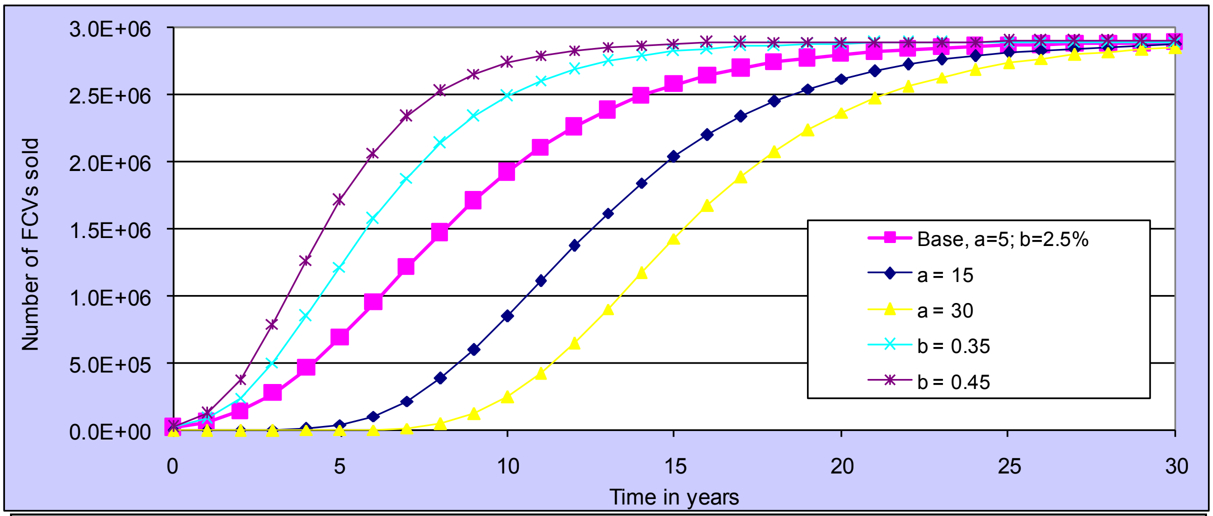
Figure 5-18: Sales figures of HEVs in the USA [http://www.hybridcars.com/]

This is confirmed by several IEA case studies on the market penetration of new energy technologies. [IEA/OECD, 2003, p. 106] Technology diffusion depends on many issues which are naturally not equally distributed nor do they present any other rational characteristics. Examples are availability of information among market actors, distribution of cost and risk factors associated with the new technology or public support (e.g. financing, standards). [Lund, 2001, p. 27] Because of the logistical nature of the technology adoption curve, it is difficult to see in the early stages whether a hype on a technology is excessive. Nonetheless, there are approaches to model the diffusion process in an analytical way. For example, the Gompertz-function, derived by Benjamin Gompertz from the logistic function, is a mathematical model for a time series, where growth is slowest at the start and end of a time period. Thus, the Gompertz-function describes, in particular, the early market penetration phase and could be used to visualise market penetration scenarios. [Hacker, 2011, p. 41] *Figure 5-19* shows typical curve progressions when varying the Gompertz variables. In the example, the total German FCV-market potential N was set to M2.9 cars. It is derived from the total number of cars in use in vehicles segments which are well suited to FCV-application in Germany.[217] In the base case, 10% market penetration is achieved after three years; 90% after 15 years, but afterwards it takes another 20 years to reach nearly full market penetration. However, the annual growth rate has to be sufficient to justify the parallel development of a filling station infrastructure. The graph shows clearly, that **growth of less than 2.5% p.a. would not allow to reach a sufficient number of vehicles on the road**.

[217] About M14.5 vehicles are in use in Germany in the segments middle class, upper middle class & upper class cars, all terrain vehicles and large vans. For this thesis, it is assumed that 20% of these vehicles, i.e. covering 75% of the early adopters and 25% of the early majority might adopt FCVs in the mid-term. Base: α= 5, b= 0.25.

The growth rate b may change over time as external events influence the attitude against the technology. This may be a positive influence due to increased interest in alternative fuels or negative influence, e.g. after accidents the risk perception may change. A successful market introduction may result in further success which is described in evolutionary approaches. For example, if FCVs sell well, the chances are that the introduction of new models will, again, attract more users and are further improved. In addition, attitude formation by marketing or by word of mouth may affect the adoption rate positively.

Also, the market potential N is not a constant. It may increase over time, e.g. when vehicle manufacturers introduce new models. New product features, lower fuel and vehicle prices, technology learning, cost reduction and product improvements could create new market segments and attract new customer groups for the technology. Also, spatial diffusion and, thus, a broader geographical extent may increase N. For example, if the market potential N grows by 2.5% annually, the total market potential increases from M2.9 vehicles to more than M6 vehicles (40% of the overall German fleet) in a 30 years period. The market for FCVs is limited to countries with a sufficient public H_2-infrastructure. Markets for FCVs could include California, Germany, the Scandinavian countries and the UK. The development of cheap electrolysers could allow lower pressure refuelling with locally produced hydrogen to locally fill commuting vehicles (e.g. at farms).



$f(t) = N * e^{-ae^{-bt}}$	*f(t):*	Number of products of the new technology in the market at time t
	N:	Market potential
with:	*N-f(t)*:	Remaining market potential for the new technology
	b:	Growth rate of the new technology
	a:	Shifting factor: lead time before growth starts

Figure 5-19: Influence of the growth rate a and the shifting factor b on the technology diffusion over time, base case, N = 2,900,000 [adapted from Lund, 2001, p. 28]

The lead time needed by a new technology to reach a visible market share varies from case to case. The S-curve implies that continuity may be needed until an adequate penetration rate is reached for a permanent and moving market transformation. [Lund, 2001, p. 29] *Figure 5-19* clearly illustrates that it is difficult to explain from early market research data the underlying trend in a market transformation process. Nonetheless, there are some characteristics of diffusion:

- The early stage of market development is critical to the further success of the new technology on the market, this is indicated by the lead time to reach significant growth,

- Small initial effects can have large long-term delaying impacts,
- Early users may lock-in the market into a deterministic growth mode. Increasing sales numbers may lead to a self-reinforcing situation in which increasing market share leads to a more attractive product, e.g. by better provision of filling stations and more FCV models. This, in turn, would lead to further increased sales and market share. This “virtuous cycle” may result in the **lock-in of the technology**. Once lock-in occurs, no existing technology can effectively compete, only significant change in technology, consumer taste or other market factors may unlock the market again. [Cowan, 1996, iv]
- In the **early stage of diffusion, policies may still make a difference**; once a product is established on the market it will be more difficult to have influence.

However, the results of the Product-Innovation-Cycle remain rather qualitative than quantitative as the location of the inflection point curve and the future slope of the curve depend on future events. The cycles are based on sales histories exhibiting diverse past patterns. Furthermore, even after FCV-sales may have started, the analyser will not be able to say what stage the product is in. A product may appear to be mature when it has actually only reached a temporary plateau prior to another upsurge. In addition, the cycles’ pattern may be the result of marketing strategies rather than an inevitable course that sales must follow. In any case, as a planning tool, the cycles help to characterise the main marketing challenges in each phase of H_2FCV-technology life and to develop major alternative marketing strategies. As a control tool, the concept helps to measure product performance against similar products launched in the past. [Kotler, 1997, p. 362]

Learning through market experience usually reduces the price of a product, which influences the dynamic of competition among technologies. **Experience curves** depict the product price over cumulative sales (expressed in pieces or cumulative capacity in the case of energy technology). These units are used to measure the experience accumulated within the industry. Large experience is a sign for technology maturity. The experience curve usually follows an exponential equation, i.e. product costs decline systematically by a common percentage each time that volume doubles. In a double-logarithmic diagram a progressive decreasing straight line is obtained. [IEA/OECD, 2000, p. 9-10]

$P(t) = P_0 * X^{-E}$	With:	P_0:	Constant: Equal to the price at one unit of cumulative sales.		
		X:	Cumulative sales;	E:	Experience parameter (E>0).
$PR = 2^{-E}$		P(t):	Price at time t;	PR:	Progress ratio.

The learning-curve relationship depicts that increasing a company’s sales volume of a standardised product and market share will also bring cost advantages over the competition. For an existing technology, it is possible to derive a rule of thumb on the price reduction achievable through learning, e.g. the generally accepted formulation of the solar industry’s learning curve states that prices of solar modules will fall 19% each time production volumes double, but this rule makes no predictions about how quickly volumes will double.[218] The change in price at doubling the cumulative value is called **Progress Ratio,** the **Learning Rate** is (100 – Progress Ratio). If progress is a constant, it means that younger technologies learn ‘faster’ from market experience than old technologies as they need fewer increases in sales to reduce the price.

Naturally learning takes place at the level of companies depending on the single producer’s own experience. This is referred to as **proprietary learning,** as opposed to **spill over learning**, where producers can also gain from their competitors' experience. There are various

218 http://web2.cc.utexas.edu/sustainability/pssc/symposium/2011/2/, 01.02.2013

channels for such spill-overs of H_2FC-technology knowledge, e.g. reverse engineering, inter-firm mobility of workers, proximity (industry clusters) or learning on sub-contractor level. When the first FCVs are available on the market, producers lagging behind technologically will be likely to dismantle the FCVs of their competitors or purchasing technology from independent component or system producers. With more companies entering the market, the use of third-party intellectual property will continue and increase. Inter-firm mobility and poaching of highly-skilled workers is regularly observable in high-tech industries. Car technology clusters like Detroit or Stuttgart and common sub-contractors such as Bosch or Delphi facilitate learning spill-over. The AFCC, CEP and CaFCP partnerships are other locations of spill-over learning. [Schwoon, no year, p. 2-3] In addition, the sale of smaller high-technology FC-developers to larger or dedicated companies is ongoing.

Existing data shows that experience curves provide a rational and systematic methodology to describe the historical development and performance of technologies. Learning curves may also be used to assess the prospects of future improvements of a technology. [IEA/OECD 2000, p. 15] The learning curve of the new technology and the price for the incumbent fossil technology meet at the **cumulative capacity** needed to make the new technology competitive. The learning investments are described by the cumulated price difference of the new and incumbent technology multiplied with the cumulative capacity. Carbon prices would increase incumbent technology prices, reducing the price gap and the cumulative capacity at which new technologies become competitive. [IEA, 2008, p. 204] The IEA uses learning curves to predict the total investment needs or deployment numbers necessary to bring down prices to competitive levels. The resulting technology deployment numbers **are very sensitive to assumed learning rates**.

The IEA 'FC drive system model' uses costs of 750 USD/kW (2008) and a learning rate of 22%, the **cost target for commercialisation is given with 50 USD/kW**. [IEA, 2008, p. 208] For the calculation of the cumulative capacity for the FC drive system it is estimated that in 2008 about 15 MW of FC were shipped for transportation purposes. [DOE, 2011, p. 10] With this figure P_0 is calculated at 23.6 kUSD/kW. At the given learning rate of 22% the cumulative capacity is 29 GW, i.e. cost competitiveness would be achieved after production of about k320 FCVs (e.g. the Mercedes B-class F-cell contains a 90 kW PEMFC). This equals about 0.5% of the German and the Californian car market. It has to be considered that only small changes in the learning rate significantly influence the location of the break-even point. With an assumed learning rate of 14%, the break-even would shift to G21 FCVs.

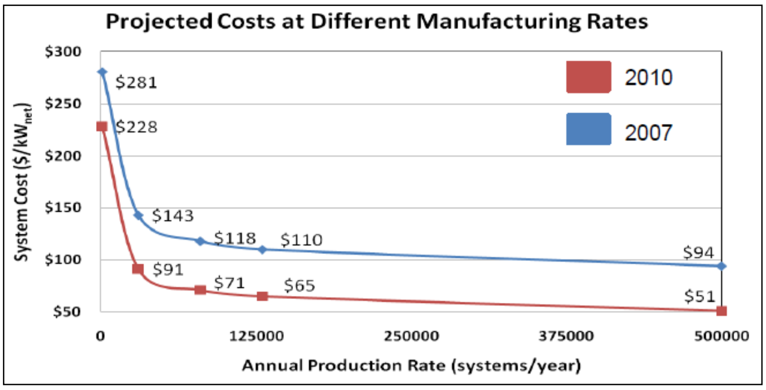


Figure 5-20: DOE projected costs of 80-kW$_{net}$ FC-system at 1, 30, 80, 130 and 500 k-units/year [DOE, 2010; DOE, 2011, p. 9]

Within the DOE Hydrogen Program the costs for an 80-kW$_{net}$ automotive H_2PEMFC-system based on 2010 technology are projected to be USD 51/kW when manufactured at a volume of k500 units/year. (BoP-costs, incl. system assembling and testing 26 USD/kW; stack costs 25 USD/kW). This would be a cost reduction of 80% since 2002. The calculated learning rate is 15.4% (11.5%) based on 2010 (2007) figures, (see *Figure 5-20*). Thus, in reality learning has improved. The 2015 DOE cost target of 30 USD/kW would be achieved only after M4.5 units are sold (the unit price would drop below 40 USD/kW at M1.4 units). For comparison, the learning rates of the McKinsey and ORL scenario, see *Figure 4-52*, have been calculated to 16% and 12.9%, respectively. A recent study on SOFC-production found learning rates between 14% and 17% for the early pilot phase and for full system fabrication between 16% and 19%. [Rivera-Tinoco et. al., 2010, p. 263-272] Another study found learning rates of 20% for residential and 18% for non residential stationary FC-applications. [Itron, 2011, A-25]

Figure 5-21 shows the learning rates of various new and incumbent distributed energy technologies. Some emerging technologies like fuel cells have very aggressive learning curves. This rapid learning occurs because new technologies with low volume production can see faster benefits from lessons associated with improvements in production. Conversely, well established technologies such as ICE and gas turbines have rather flat or even negative learning curves. [Itron, 2011, A-3]

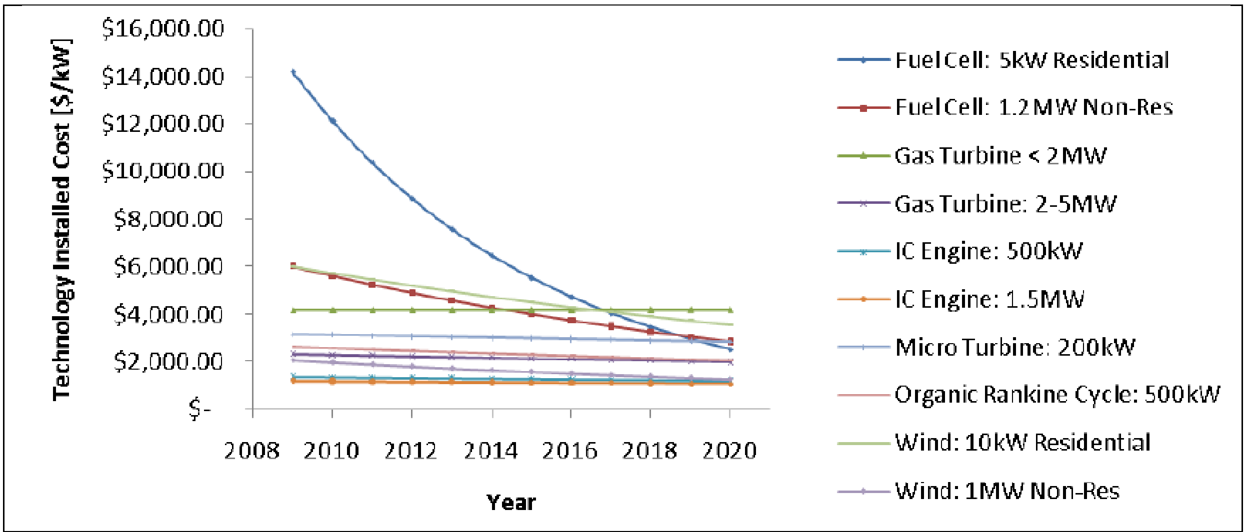


Figure 5-21: Learning curves of different distributed energy generation technologies [Itron, 2011, A-3]

During recent years, government sponsored and private industry R&D decreased FC-costs and improved system durability and performance. The losses of the industry are declining. Also, R&D expenditure declined from 126 MUSD in 2007 to 62 MUSD in 2010 for the five largest Northern American FC companies as companies have left the basic research phase. [DOE, 2011, p. 5] For example, FuelCell Energy may be the first stationary FC-manufacturer to generate a quarterly profit. The company targets to provide 210 MW FC-capacity p.a., electricity generation costs shall decrease to 0.09-0.11 USD/kWh.[219]

Finally, it should be mentioned that experience has different properties as a market entry barrier than economies of scale, although they often coincide. The presence of economies of scale always leads to a cost advantage for the large scale firm over the small scale firm, presuming that both have the most efficient facilities, distribution systems, service organisations and other functional activities available. This advantage results from the spreading of the fixed costs of operating the efficient facilities over a larger number of units. However, economy of scale may penalise the large-scale firm with facilities designed to reap scale economies. The production is usually highly standardised, models change less frequently and the product line offers less flexibility. The capabilities of the firm to handle innovation is

[219] http://www.fuelcellenergy.com/about-us/history/; http://qz.com/135032/fuelcell-energy-fuel-cell-profit/; 07.08.2014

weakened. This reduces the flexibility to adapt to new technologies. The focus on scale economies may cloud the perception of new technological possibilities.

The existence of experience does not ensure a market entry barrier for others as long as this experience is not proprietary. Through copying, hiring competitor's employees or purchasing the latest machinery from equipment suppliers or know-how from consultants etc. experience may become available to other market entrants. Even worse for the pioneer, experience may accumulate more rapidly for the second and third firms in the market because followers can observe some aspects of pioneer's operations. Experience as a market barrier may even be nullified by product or process innovations leading to a substantially new technology and thereby creating an entirely new experience curve. [Porter, 1980, p. 15, 16]

In addition, learning rates only generate a real cost reduction if the new, better FC-system can be integrated into the vehicle manufacturer's line without large changes. However, cost reductions are mainly expected from MEA, catalysts and the large scale FC system production; this influences FCV-production only indirectly. Because system size and weight is expected to decrease, this may even ease production.

Finally, FCV-technology has achieved learning rates of between 13% and 20% in the past; a continuation of these learning rates appears possible and would heavily contribute to the buy-down of FCV-costs. For the concrete market introduction of stationary and mobile technology more investments are necessary. The main investor in mobile FC market introduction is the car industry. Section 6.2 is aimed at qualifying investments already carried out. The evaluation of future readiness to invest is difficult to carry out. Stock analysts are currently evaluating Ballard (hold/buy) Hydrogenics (buy) and FuelCell Energy (hold/buy). In the stationary sector trends are more obvious. The ongoing concentration in this industry and the trend to cooperation or acquisitions by financially strong major groups indicates a strong business interest in the technology. New investors such as POSCO, Doonsa, NRG etc. have the financial power to support the market penetration of FC-technology. The government is also an important investor for the technology. The German government is currently negotiating the ongoing implementation of the NIP and the cofinancing of the H_2-mobility initiative. The Californian government approved financial means for supporting about 100 stations (see section 3.2.2). FC technology development is also being further co-financed. The funding programmes have changed towards supporting market introduction; no withdrawal of funding or political support has been observed.

6 Market development perspectives of hydrogen fuel

Radical innovation is a complex and uncertain endeavour. The incumbent industries, their products and processes are well aligned with existing institutions, sales networks and consumer demands. Stakeholders that develop and commercialise an H_2FC-innovation which does not match the criteria which are shaped by current practices, fight an uphill battle. It is therefore reasonable that the stakeholders are often reluctant to be the first to engage in that 'battle' and are waiting for the other to act first. This is especially the case for the fuel/energy/ drive train system innovation initiated by H_2FC-technology in which multiple stakeholders from various industries need to co-operate and co-ordinate their efforts. In this situation, actors may only move once they are assured that others will play along. [Bakker et. al. 2012, p.1]

1. Literature Analysis
- **Aim**: Description of FCV development history: success and failure, alliances, forecasts on technology progress etc.
- **Approach**: Analysis of publications in magazines, Internet and other media
- **Results**: Important milestones, role of stakeholders, technology learning and selection process

2. Patent Analysis
- **Aim**: Evaluation of R&D topics and main actors, analysis of status of technology development
- **Approach**: Statistical analysis of patent applications at EPO using esp@cenet database
- **Results**: Identification of main actors and co-operations in H_2FC-R&D, state of technology development in main R&D fields

3. Delphi-Analysis
- **Aim**: Discussion of the possibilities to actively shape the market introduction of H_2- fuel
- **Approach**: Delphi-analysis to investigate and qualify the opinion of an expert panel on an uncertain problem
- **Results**: Ranking of technologies, timing of changes in vehicle market, identification of technology promotion measures etc.

4. Application of Porter Model of 5 forces
- **Aim**: Evaluation of impact of driving and inhibiting factors on the market success of H_2FCV and other substitute vehicle technologies
- **Approach**: Adaptation of 'Porter Model of Five Forces' on competing vehicle technologies and fuels in a changing environment
- **Results**: Qualification of role, synergies, antagonisms and impact of driving factors and drawbacks

5. Description of a possible H_2FC-technology market introduction pathway
- **Aim**: Showing one deployment pathway for hydrogen fuel and FCVs (cars)
- **Approach**: Summarising all results in a possible pathway, time axis until 2030 and 2050, including industry or policy targets on FCV/H_2-filling station numbers, legal requirements, RDD activities, H_2FCV price targets, other H_2FC technology drivers
- **Result**: Pathway attached to preconditions along the time axis

Figure 6-1: Approach for the evaluation of hydrogen fuel market perspective

The main FCV-marketing strategies are negotiated behind closed doors. The public is informed with statements to serve the industry's interests whenever needed. This may cause a media hype on the technology that does not reflect the state of technology or market development. In any case, technological hype can have both positive and negative effects. On the one hand, it attracts funding and support for technology development; on the other hand, unmet expectations might result in disappointment and subsequent withdrawal of support. [Bakker, 2010, p. 1]

For a realistic assessment of the market development perspectives of hydrogen fuel independent information and assessments are necessary. Due to the uncertain nature of the future, the bias of nearly each piece of information published as well as the reluctance of the main players to reveal detailed information on their state of H_2FC-technology development, strategies and future targets for a possible pathway of H_2FCV-market introduction are deduced from the following sources within the framework of this thesis:

- An analysis of the policy and legal framework conditions, see section 3,
- Progress in standardisation, technology research and demonstration programmes, see sections 3.4 and 4.1,
- Achievements from technology development and consumer customisation in neighbouring markets, e.g. markets for NGVs, HEVs, PEVs and BEVs, see section 4.2,
- The economic surrounding characterised by the global population development, fuel prices and overall economic situation, see sections 3.4 to 3.6,
- The activities of main stakeholders in the process of H_2-fuel marketing, see section 5.

The status quo of the market introduction of H_2-fuel and its deployment perspectives are evaluated in the following using the three main tools of: literature analysis (section 6.1), research and patent analysis (section 6.2) and Delphi analysis (section 6.3). Aim, approach and anticipated results are described briefly in *Figure 6-1*. Interim results are consolidated using an adaptation of the Porter Model of five forces (see section 6.4) and, finally, the preconditions for a future deployment pathway are described (see section 7).

6.1 Literature analysis of the status quo of hydrogen fuel and FCV market

The understanding of the history of the H_2FC-technology development is important for forecasting future developments. The stakeholders of the technology themselves regularly publish own assessments of the state of the technology or forecasts on technology development and introduction timelines. These publications reflect insight knowledge and are a very important information source for any predictions on future market development. However, the announcement on any R&D-progress of vehicle manufacturers follows also other intentions besides information purposes. These declarations are normally also driven by marketing purposes or are aimed at demonstrating the own strength in the technology field. The publication of a breakthrough in a certain technology field by one company forces others to react and to show off as an innovative company in the public eye and to the shareholders, too. This competition pressure regularly ignites a mere firework of similar announcements and puts the spotlight on certain technologies independent of their real development level. In this way, technological hype is generated. For example, FC-technology was hyped with various announcements between 1999/2000, see annex 8.3. The concrete results of most of the announced projects were meagre. In particular, the hype on hybrid technology, triggered by the successful market introduction of the Toyota Prius, illustrated the pressure on the R&D departments of other premium vehicle manufacturers which could be induced by public opinion.

In general, a technology hype does not care about a realistic time horizon for technology introduction and the hurdles which still need to be overcome before any successful market introduction of the H_2FC-technology can be thought about. Therefore, the new technology is in great danger of falling flat in public before the first vehicles suitable for daily use are available on the market. However, an innovation may also need hype to gain legitimacy and credibility in its early stages of development. **Innovation relies not only on scientific and technological achievements and breakthroughs, but also on expectations of future potential**. In particular, these expectations on progress in H_2FC-technology support the collective action of researchers, engineers, firms and funding agencies currently existent in strong and well organised associations, e.g. CEP and CaFCP. [Bakker, 2010, p. 1]

This work is carried out by people who push H_2FC-technology over barriers, speak for the technology and acquire the necessary funds to continue technology development without a short-term achievement of a return in investment. (The effort of these organisations and enthusiasts may be measured by the amount of funding acquired for the technology.) The "enthusiasts" have linked their personal carrier to the success of the technology. Examples include Ferdinand Panik of Daimler or Wolfgang Strobl, BMW. Highly specialised companies and organisations such as Ludwig-Bölkow-Stiftung or NOW have aligned their existence to the continuous development and fundraising for new H_2FC-projects. Also, public bodies such as the EC/DG TREN have committed themselves to the success of H_2FC-technology through a long history of funding huge projects.

In particular, technologies with the promise of a solution for long-term unsolved problems and a need for a long preparation time are keen to trigger hype. H_2FC-technology is a good example from previous years. Technologies with a shorter time to market such as mobile phones or other consumer applications are not that concerned. The Gartner "hype cycle" depicts the connection between hype, expectation in market success and hype-disappointment. It positions technologies on a time scale to make recommendations on the right timing for strategic investments. Even though hype cycles take on different shapes and sizes for different technologies, the concept of the Gartner cycle provides a clear illustration of the basic dynamics.

After a first technology trigger, expectations in the technology increase sharply and this, in turn, is supported by optimistic predictions and the denial of technical shortcomings. This creates hype up until the inflated expectations peak. After the peak is reached, disappointment about the realistic capabilities of the new technology gets the upper hand and, subsequently, the visibility of the technology drops rapidly, which then results in the trough of disillusionment. At some point in the future when the technology has been developed further, possibly merging with other advanced ideas, set within an economic context or even business case, then the technology can be realistically assessed and, slowly but surely, visibility will increase again accompanied by more modest expectations. The technology might make its way to the market and visibility will stabilise at a level depending i.e. on mass- or niche market introduction. [Bakker, 2010, p. 1-2]

Gartner's analysis on "Hype Cycle for Smart City Technologies, 2012", (see *Figure 6-2*), assumes that technologies for the 'H_2-economy' and 'EV-infrastructure' initially begin to garner interest; PHEV/EVs for smart grid applications have outpaced the peak of inflated expectation. Electric vehicles are arranged in the "Trough of Disillusionment". John German, program director for the International Council on Clean Transportation environmental policy group made the same arrangement for FCVs in June 2013, "*We're now in the 'trough of disillusionment' for fuel-cell vehicles*."[220]

Annex 8.3 documents publications on the development of the FCV-market and the H_2-economy from related industry or institutes. The statements are classified and evaluated. If possible, proactive statements from the past are compared with achievements that could be

[220] http://www.bloomberg.com/news/articles/2013-06-26/toyota-seeks-prius-like-success-with-2015-fuel-cell-model; 15.11.2015

realised in the meantime. Information sources include special (scientific) journals, press releases, conference proceedings and internet publications etc.

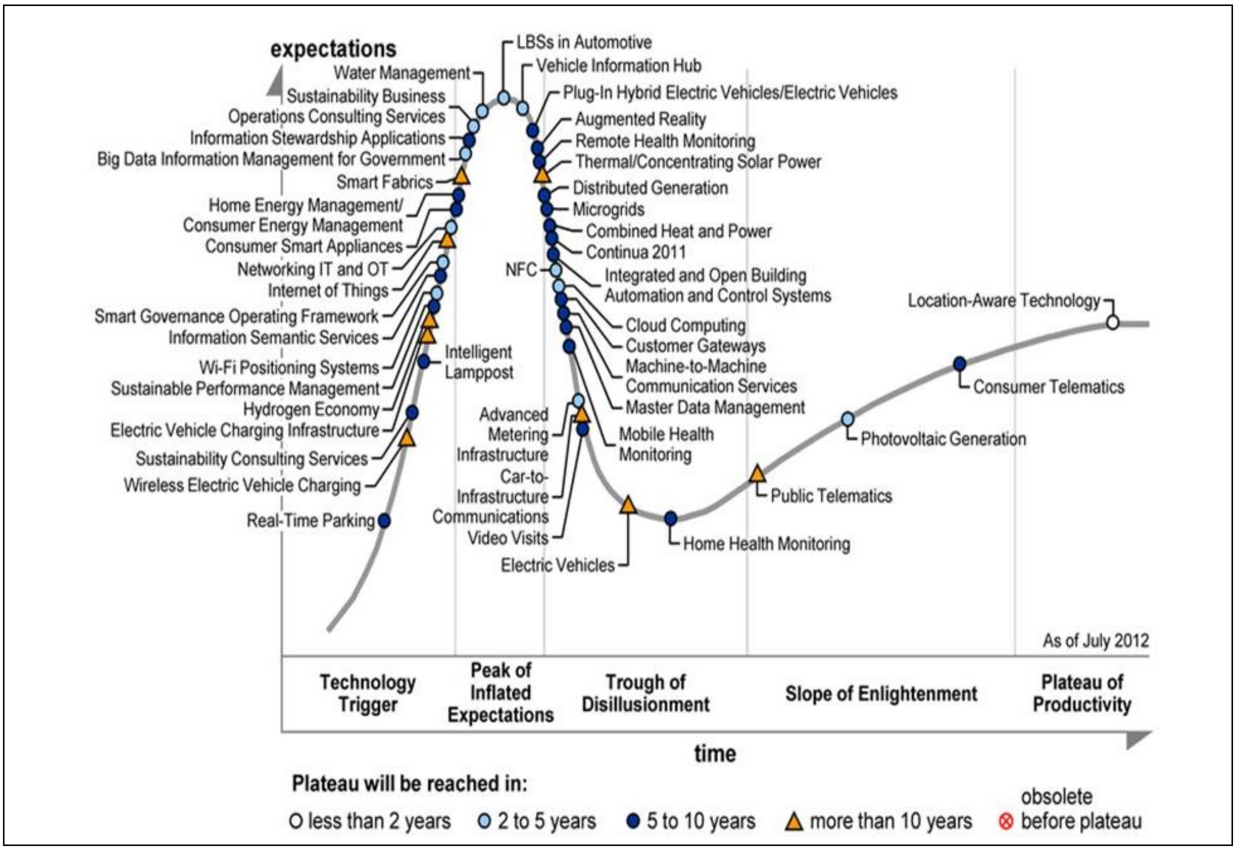


Figure 6-2: Gartner Hype Cycle for smart city technologies, 2012[221]

The industry repeatedly announced a timeline for the FCV market introduction in Germany (see *Figure 6-3*). In parallel, more or less mature FCV-prototypes were presented to the public (see *Figure 6-4*). The single company statements can be clustered as follows:

Hype of the late 1990s: Daimler, GM, Ford and Opel announced an H_2-vehicle ready for serial production by 2004/2005. These vehicles were intended to rely on reforming, a technology that was abandoned after 2000. The first H_2FC-buses were commissioned, e.g. in Erlangen (Nebus). The first joint FC-projects from the car, mineral oil and supply industry started, e.g. Ford and Mobil, Daimler/Ford/Ballard as well as a French consortium around Renault and PSA. Several (H_2)-associations were founded such as the French and Swedish Hydrogen Association, the Canadian National Fuel Cell Research and Innovation Initiative or the European Hydrogen Association. BP accepted anthropogenic CO_2-increase and climate change; Shell founded Shell International Renewables and Shell Hydrogen B.V. (today integrated to Shell Deutschland).

Reorientation in 2000: Manufacturers looked for the right fuel to use in FCs. The VES was founded in 1998. VW presented the LH_2-Bora, BMW launched 15 H_2ICE vehicles, Opel showed LH_2-ICE Zafira, Daimler launched the Necar 5 with methanol reforming and Ford presented the FC Focus at the EC.

Concentration on H_2FCs between 2001 and 2003: German manufacturers agreed on hydrogen as a fuel for automotive FC-application (VES, 2001). GM was initially reluctant to

221 http://www.urenio.org/2013/01/05/hype-cycle-for-smart-city-technologies-and-solutions-2012/, 01.08.2013

concentrate on direct H2-FCs, but followed later. VW paused its public FCV-activities. **The advocates of FCVs (Daimler, Toyota, GM/Opel) concentrated on the development of H2FCVs to be marketed until 2010**. The CEP was founded in 2002 and various H2-FC/ICE vehicles were put into demonstration projects.

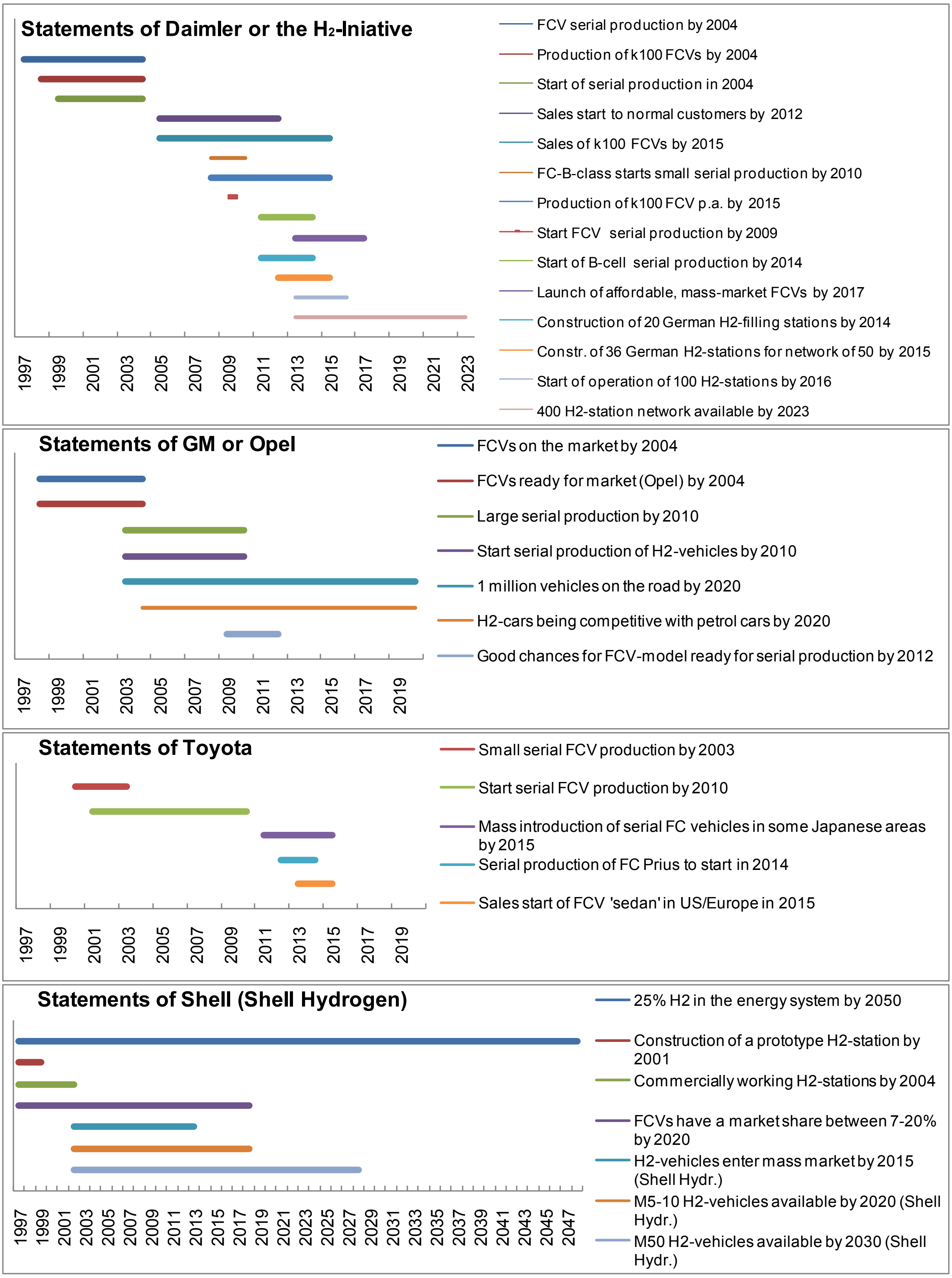


Figure 6-3: Timeline for H2FCV-marketing (starting point: year of announcement, final point: predicted year of achievement), see Annex 8.3 for details

The number of H_2FCV-prototypes reached its heyday (see *Figure 6-4*). The first FCV (Honda) was homologated in Japan and the US. 70 MPa technology was introduced in test vehicles. In 2003, PowertechLabs, a Canadian technology consultant, co-ordinated a multi-manufacturer project for 70 MPa technology development and standardisation. GM and Daimler opened the next round of announcements for FCV marketing timelines (approximately between 2010-2015).

Looking for a down-to-earth approach for FCVs, 2004-2009: in 2003, GM announced (based on real-life experience) that it would start serial production by 2010 and would already have M1 vehicles on the road by 2020. The first FCV was transferred to a customer for validation in Germany in 2004 and global number of FCVs installed reached 500 in 2005. In 2005, Daimler announced it would start serial production with k100 units p.a. by 2015. Shell (Hydrogen) predicted H_2-vehicles would enter the mass market by 2015 and would be competitive with petrol vehicles by 2020. The cooperation of the industry with the government strengthened to support standardisation, research and infrastructure development. The first German "Parliamentary Evening" on H_2FC-technology was organised in 2004. In California (CaFCP) and Germany (Linde) concepts were published for an area covering fuelling station network in 2004/2005. Already by 2003, the EC announced spending 2.8 G€ on H_2-R&D between 2005 and 2015; StorHy- and HySafe-project contracts were finalised in 2004. The German NIP programme (2007-2016) has a budget of 700 M€, the annual funding volume was about 80 M€ between 2010-2012.[222] By 2007, the industry was able to present “full” FCVs which could be transferred to a larger (test) clientele. The construction and testing of H_2-filling stations continued and the first statistics on global station numbers were introduced. FC-applications for forklifts (H_2-infrastructure), campers, boats etc. (operated on methanol) entered the market introduction phase in niche markets.

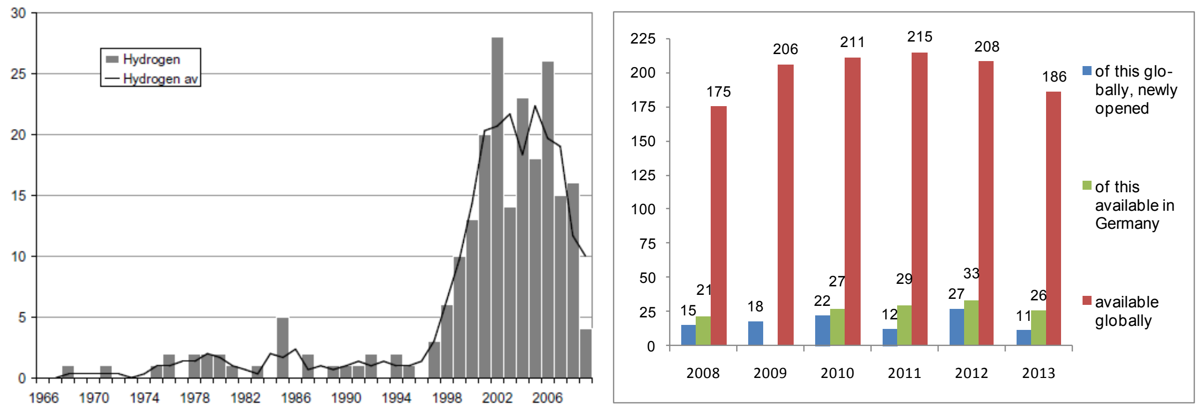


Figure 6-4: H_2FCVs prototypes p.a., (left), H_2-fuelling stations available (right)[223]

The **early commercialisation of FCVs (2010- to date)** is projected by leading vehicle manufacturers (Daimler, Toyota, Honda) in the 2015-2017 timeframe. Daimler and other industrial stakeholders selected Germany as a lead market in Europe to promote the market introduction of FCVs. Older H_2-stations which do not fulfil the standards of the new SAE J2601 are being taken out of operation, new stations are hesitantly put into operation.

Daimler became a spokesman for the German market introduction: after the 2009 world tour, Daimler shortened the timeline for market introduction by one year to 2014. Only shortly later, Daimler planned to start B-class F-Cell small batch production for 2015. In January 2013 Daimler postponed the production start to 2017 due to difficulties in achieving price

222 http://www.now-gmbh.de; 12.08.2014

223 Bakker, 2010, p. 3, http://www.netinform.net/h2/h2stations/Default.aspx, 08.08.2014

targets and a missing infrastructure. [Krust, 2013] **Daimler fostered old and new alliances with Ford and Renault-Nissan** to increase scales and to reduce costs, see *Figure 6-5* for an overview on current automotive cooperations. **Ford** had to withdraw from its large FCV-programme due to financial problems, but is currently recovering. Daimler entered an agreement with Linde to build 20 H_2-stations in 2011-2014. The "H_2-mobility initiative" investigated to extend the H_2-infrastructure to 100 stations by 2017 and to about 400 H_2-stations by 2023 (investment of 350 M€) together with the energy industry. Negotiations on governmental co-financing are ongoing. The Joint Venture "H_2-mobility", founded in 2015 should erect these 400 H_2-stations by 2023 and operate them. [http://h2-mobility.de/#; 11.09.2015] **Nissan** joined Daimler and Ford in their joint FC-program. The general cooperation with Renault-Nissan offers Daimler access to the small vehicle platforms of Renault which shall be used for the Smart as from 2014/15 onwards. [Schmidt, 2014]

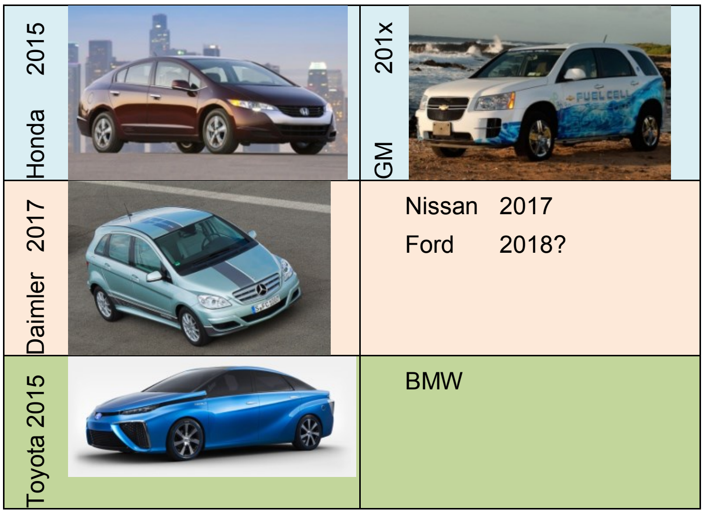


Figure 6-5: Automotive FCV-co-operations and date of expected FCV-launch[224]

Toyota 2012 concentrates on the market introduction in Japan until 2014/2015 and in the USA and Europe in 2015. Toyota claimed it was building on Prius experience and would become the FCV market leader. **Honda and Hyundai** declared they would follow Toyota into the market. This move brought H_2FC-technology back into the spotlight in 2013. Frost & Sullivan expects the number of FCVs in Japan and South Korea to increase from 600 units in 2011 to k58 units by 2020, mainly in the medium passenger car segment. In particular, cities in Japan such as Tokyo, Osaka, Nagoya, and Fukuoka and Seoul and Ulsan in South Korea have been targeted by OEMs for the commercialisation of FCVs. The Japanese and South Korean governments play a key supporting role in the commercialisation of FCVs. They offer R&D support and subsidies for H_2-stations. In 2011, 11 H_2-stations were operational in Japan and South Korea. Frost & Sullivan expect Honda to be the leader in the FCV-market in Japan and South Korea in 2020 with more than a 40% market share. Hyundai and Toyota are expected to command market shares of about 17%.[225]

Toyota has kept media interest high by publishing information on its FCHV piece by piece at Tokyo Motor Show 2013 and the Las Vegas Consumer Electronics Show 2014 etc. Among high-gloss photos, an "Erlkönig" during test driving has been launched. Toyota offensively answered the provocation of Tesla's Elon Musk who blamed FCs in October 2013. This opened "a war of words" which reflects the competing situation of BEVs and FCVs. The Toyota FCV market introduction strategy adopted the successful Prius strategy; also the same managers are involved. On the Japanese home market Toyota Tsusho Corporation (51%) and Air Liquide Japan Ltd. (49%) established a joint venture "Toyota Tsusho Air Liquid Hydrogen Energy Corporation" to build Japan's first commercial network of H_2-stations to be opened in Nagoya and nearby Toyota City in 2014.[226] Linde opened a small-series production

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224 http://automobiles.honda.com/fcx-clarity/exterior-photos.aspx; http://www.daimler.com
225 http://www.frost.com/prod/servlet/press-release.pag?docid=270511773, 02.01.2013
226 http://www.toyota-tsusho.com/english/press/detail/131028_002371.html, 17.12.2013

line for H_2-fuelling stations (capacity to build 50 stations p.a.) in Vienna in July 2014. Linde announced an order for 28 stations from Japanese gas trading company Iwatani, which put the first of its Linde stations into operation near Osaka also in July 2014.[227] In addition, the California Energy Commission awarded 4.3 MUSD to Linde North America to construct two retail H_2-fueling stations at Oakland Airport and on Toyota owned property in San Ramon. Several more stations are ordered at different manufacturers, e.g. for Paris, London etc.[228]

Currently, an FC component manufacturing facility (manufacturing start in 2015) is under construction in Pohang, South Korea that is owned by POSCO Energy. General Electric is building an FC pilot development and manufacturing plant in New York.[229] The German BWT-Fumatech opened a new membrane production plant in Bietigheim-Bissingen in 2014. Japan installed k50 CHPs in 2013 and has a production capacity of k75. The US Fortune 500 companies operate already k50 FC forklifts. The VDMA estimated that k7.5 FCs have been produced in Germany in 2013 and that this number would increase to k32 by 2015 and k300 by 2020. A turn-over of 2 G€ is estimated for the German FC-industry by 2020 (0.105 G€ in 2013). [VDMA, 2014, p. 5, 7, 10, 15] First stock-listed companies managed to reach the break-even and reached a profit per share, e.g. Heliocentris, SFC.[230]

In addition, **Honda built an FC-alliance to reduce costs with GM in 2013**, thus forming a partnership between two of the strongest FCV technology companies. GM and Honda have cross-licensed their intellectual property and know-how as part of the partnership deal. Honda plans to go more broadly to market in the 2015 time frame with an FCV; GM has yet to announce plans to go to market. Mark Mathias, GM Director of FC R&D, stated at the partnership at SAE 2014 Hybrid & Electric Vehicle Technologies Symposium:

“We have vehicles now that work and can be durable, it’s really now about making a business out of the technology. Obviously it involves both the vehicle and the infrastructure and the hydrogen supply, so there are a lot of elements to this.” “Fuel Cell Electric Vehicles are currently the most promising 300+-mile range, quick refill, petroleum/emissions-free option. If you want all of those elements, this is the best option we see. We don’t see Li-ion, Li-air getting us to this point.”[231]

After abandoning its H_2ICE demonstration (2009), **BMW** concentrated on the development of an SOFC-APU in cooperation **with Delphi (2010)**. BMW planned to enter a cooperation with GM on FC R&D (2011), continuing earlier approaches of joint 70 MPa technology research. This cooperation was terminated in 2012 and **BMW entered an agreement with Toyota** (2013) to share their FC-technologies and jointly develop a fundamental FCV-platform by 2020; this will include not only an FC stack and system, but also a hydrogen tank, electric motor and supporting battery system. BMW profits from Toyota’s hybrid experience in exchange for diesel technology.[232]

VW has a reluctant position concerning FCs. Nevertheless, VW regularly states against the trend and presents progress in H_2FC-development. VW announced it would market a FCV by 2020. The last FCV presentation dates back to 2007; since then only NGVs and BEVs have been presented. VW recently entered **a cooperation with Ballard** on engineering services

227 http://www.dgap.de/dgap/News/corporate/linde-linde-starts-smallseries-production-for-hydrogen-fuelling-stations-news-with-additional-features/?newsID=809205; 12.08.2014

228 http://www.gasworld.com/hydrogen/100792.subject; http://www.gasworld.com/regions/north-america/california-commissions-hydrogen-stations/2004132.article; 12.08.2014

229 http://www.bizjournals.com/albany/news/2014/07/22/general-electric-is-building-a-fuel-cell-pilot.html; http://www.fuelcellenergy.com/about-us/manufacturing/, 12.08.2014

230 http://www.wallstreet-online.de/diskussion/1181819-1-10/brennstoffzelle-schafft-break-even, 31.8.2014

231 http://www.greencarcongress.com/2014/02/20140221-mathias.html, 2014

232 http://www.fuelcelltoday.com/news-archive/2013/january/toyota-and-bmw-to-jointly-develop-new-fuel-cell-vehicle-platform-for-2020; 23.01.2014

to support its FC research programme. Ballard's automotive FC know-how has been split-off to the AFCC, thus this cooperation still needs to prove whether or not it could be powerful.

This last cooperation agreement may conclude the recent building of alliances between the energy and chemical gas companies, FC and vehicle manufacturers. Hyundai and Hydrogenics are the only companies without a partner; the other main players are committed.

In June 2013, **Fiat** bucked the industry trend towards H_2FCV by turning its back on the technology after three generations of development. Fiat believes that FCs are too short-lived, as hydrogen which has been reformed from fossil fuels still contains small amounts of CO which slowly poison the platinum catalysts. Fiat also argues that the technology offers no huge efficiency gains over a diesel engine when the energy used to reform hydrogen is taken into account. Fiat's preference in the short term is for compressed natural gas (CNG).[233]

In the meantime, the announcements for market entry of Toyota, Honda, Hyundai, Daimler and, to some extent, GM have become much more precise. They are backed by concrete negotiations and inter-industry agreements with the government on the erection of an H_2-infrastructure. FCVs are monofuelled, investment costs both for FCVs and infrastructure are high. The industry is aware that only a quick regional market entry with a significant number of FCVs provides the necessary impact to justify and reasonably utilise a growing H_2-infrastructure which is a precondition to any FCV sales. The industry has learned the lesson that a well-balanced (numbers and regional distribution) relationship will not emerge on its own, but needs inter-industry organisation.

The evaluation of the value of the current market introduction announcements of the Big Five is not possible: it will depend on the interaction of the market forces and the development of the external framework conditions, to determine whether the H_2FCV-market will gain momentum. However, based on the history of not implemented announcements, it seems unreasonable that without ongoing political pressure the necessary investments are made. The ongoing commercialisation of FC-applications in the leisure segment, in material handling equipment and, more recently, in the stationary sector and for home appliances provides ground for the generation of turnover in the dedicated industry and will concretely support technology development, FC price reduction as well as a positive public attitude for the technology.

6.2 R&D effort and Patent Analysis of hydrogen fuel and fuel cell market

Knowledge about the level of investments in H_2FC propulsion technologies would give a good indicator on the prospects investors have in these technologies. This data are company secrets and R&D investment data are only published within a highly aggregated level. However, combined with sales data, it is possible to identify general 'R&D-champions', (see section 6.2.1). R&D efforts generally result in the application for and granting of respective patents to individuals and organisations. The analysis of patents applied in a certain technology field provides a picture of specific R&D focus and the main R&D-players in the industry (see section 6.2.2). However, intellectual property is sometimes also kept confidential so as not to reveal details of any strategies and to prevent other parties from taking advantage.

[233] http://www.autocar.co.uk/car-news/industry/fiat-rejects-hydrogen-fuel-cell-power, 03.02.2014

6.2.1 Research & Development investments in the automotive industry

According to the International Accounting Standard (IAS) **"Research"** is defined as an original and planned investigation undertaken with the prospect of gaining new scientific or technical knowledge and understanding. **"Development"** is defined as the application of research findings or other knowledge to a plan or design for the production of new or recently substantially improved materials, devices, products, processes, systems or services before the start of commercial production or use.[234] [EC, DG Research, 2008, p. 39] Annually, the EC publishes its "EU Industrial R&D Scoreboard" containing economic and financial data of the world's top 1,500 companies ranked by investment in R&D.

Between 2010-2012, the Scoreboard companies increased their R&D investments by an average 6.2% p.a. This happened in a global context marked by a general slow-down of net sales growth (4.2% in 2012 vs. 9.9% in 2011) and a decline in operating profits (-10.1%). EU based companies increased their **total R&D investments** (6.3%). In 2012, R&D investment for EU based companies was driven by the very good performance of Germany (9.5%), which accounted for one third of the total R&D investments of Scoreboard companies. Also in the **Automobiles & Parts Sector,** the biggest sector in terms of R&D investment in the EU, **the R&D investment growth** was considerably high (8.9% globally, 14.4% EU). [EC, DG Research, 2013 (2), p. 39] The ratio between R&D spending and net sales is defined as **R&D intensity**. It is one of the main performance figures for comparing the R&D spending of companies or for evaluating the success of R&D investments. [EC, DG Research, 2008, p. 39] The Automobiles & Parts Sector shows an R&D intensity between 2 and 5%. It is classified as "medium-high R&D" sector. Sectors with high R&D intensities such as the pharmaceuticals or biotechnology sectors achieve values of about 15%.

The automotive industry is strongly science-based and innovation is an important competitive factor. Automotive R&D is driven by stricter vehicle emissions and fuel consumption standards, product differentiation to meet customer satisfaction and cost reduction due to tougher worldwide competition including the emergence and growth of new Asian manufacturers. To succeed automotive companies need to be large enough to cope with high model development and launch costs and be able to obtain keen supplier prices or be a smaller niche specialist for higher priced cars. [EC, DG Research, 2013 (1), p. 9, 45 p. 23]

Figure 6-6 depicts the 30 automotive companies with the largest global sales in the "Automobiles & parts" and the "Commercial vehicles & trucks" sectors (hereafter referred to as automotive sector). In 2012, Toyota and VW achieved the highest sales[235] (193 M€ each). Between 2005 and 2012, Toyota generated by far the largest cumulated net sales, i.e. 24-33% more than its largest competitors GM, VW, Daimler and Ford and the largest average operating profit, i.e. 5.5% (compared to these largest competitors). Four out of the six largest automotive companies have strong FCV programmes, i.e. Toyota, GM, Daimler and Honda. They all confirmed belief in the success of H_2FCV-technology, see Annex 8.3. Hyundai, another FCV technology leader, is number eleven in the net sales ranking.

Knowledge as the driving force for innovation is a scarce resource in the industry and therefore forms an intangible asset of enormous value. The highest R&D intensity (2005-

[234] On behalf of the EC an annual "Industrial Research Investment Monitoring" is carried out. The results are published in a so-called "R&D Investment Scoreboard". Results are available according to industry sectors, the clustering to sectors is based on the ICB Industry Classification System. In the Scoreboard the R&D intensity is calculated only for those companies for which data exist for both R&D and net sales at the aggregate level in the specified year.

[235] Sales is defined, excluding sales taxes and sales of joint ventures & associates.

2012) among the vehicle manufacturers is achieved by the smaller, high-premium producers such as BMW (5.4%). Due to the comparable smaller sales, their R&D investment per vehicle is quite high. However, two mass market producers also came up with high values: Honda Motor (5.5%) and Renault (5.4%). The large companies Toyota (3.9%), VW (4.8%), GM (4.5%), Daimler (4.4%) and Ford (4.3%) have average R&D intensities. *Figure 6-7* depicts the absolute R&D investments of the 30 leading automotive companies in comparison with their R&D intensity (2005-2012). In 2012, VW had the largest global R&D spending (9.515 G€) of companies from all sectors and was the only EU based company in the top 10. Second was Samsung Electronics (8.345 G€) – which is also engaged in stationary and mobile FC-applications. Toyota, which led the ranking the two previous years, reached rank five with 7.071 G€ and Daimler ranked 11 with 5.639 G€.

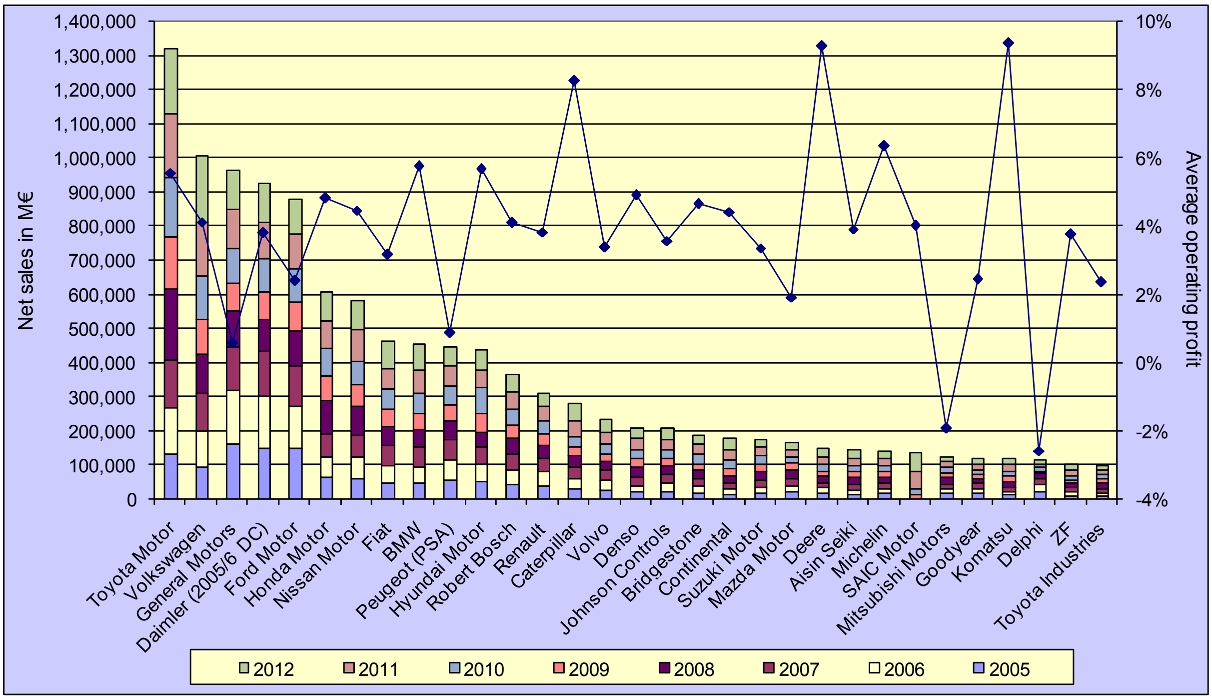

Figure 6-6: Cumulated net sales (left side) of the 30 leading companies in the automotive sector compared to the average operating profit (right side), 2005 to 2012 [236]

The R&D intensity of the automotive supply companies is generally higher than that of the automotive companies itself, i.e. Robert Bosch (8.1%), DENSO (8.6%), Delphi (8.2%), Aisin Seiki (4.8%) and ZF (5.2%) (2005-2011), because a large part of innovation and product development is performed on their side. They have a close connection to the automotive industry and the big automotive companies are shareholders in some of them. Important suppliers are the Robert Bosch Group (controlled by an independent Foundation), Denso (separated from Toyota Motor in 1949; major shareholders: Toyota Motor (24.75%)[237] and Toyota Industries (8.54%)), Delphi Corporation (founded by GM in 1994, today independent, but GM is still the largest customer), Aisin Seki (independent) and ZF (independent).

236 Own depiction, data fromhttp://iri.jrc.ec.europa.eu/research/scoreboard_2006.htm – scoreboard_-2010.htm, tables 1_3.xls, 1_7.xls; 28.06.2011: The *Scoreboard* data are drawn from the latest available company accounts. Since 2011, the Scoreboard's database has changed: commercial trucks and vehicles have been regrouped to "Industrial engineering" and it is no longer possible to select the automotive companies. In addition, only the 1,500 world largest companies are included. Operating profit is calculated as profit (or loss) before taxation, plus net interest cost (or minus net interest income) minus government grants, less gains (or plus losses) arising from the sale/disposal of businesses or fixed assets.

237 http://www.globaldenso.com/en/investors/stock/overview/index.html, 13.08.2014

There are also specialist technology developers with a focus on only a limited number or even a single technology. Ballard (last entry in the Scoreboard in 2006 with R&D investments of 64 M€) or Hydrogenics are good examples for FC-technology (see section 5.3.1.2).

The knowledge of the absolute investment figures for R&D does not yet allow a conclusion on the R&D strategies pursued by a company or its R&D focus, e.g. amount of money invested in H_2FC-technology R&D.

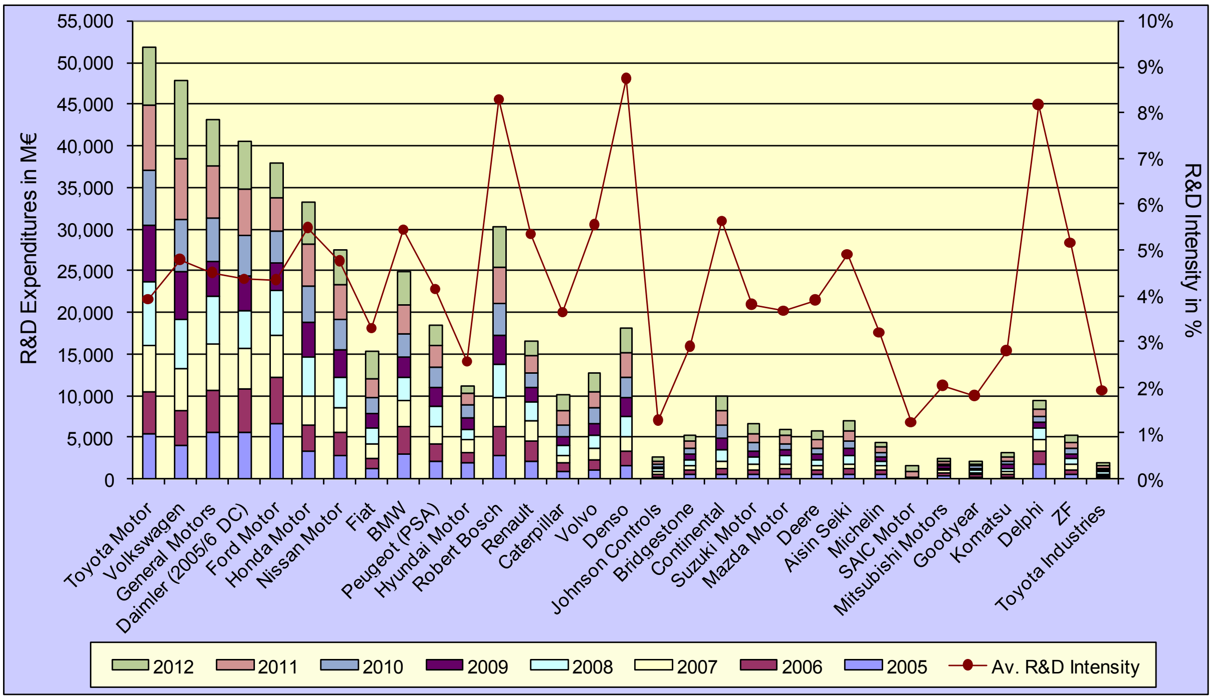

Figure 6-7: R&D investments (left side) in comparison with R&D intensity (right side) of the 30 leading companies in the automotive sector, 2005 to 2012[238]

6.2.2 Patent analysis

Company information material generally lacks detailed information on R&D strategies. Information on R&D strategies of a company and R&D partnerships in a technological field can be obtained through patent analysis. **Patents** are the most important of various Intellectual Property Rights on inventions and technologies. A patent is a set of exclusive rights granted by a State to an inventor. It confers **a territorial monopoly right** to the owners for a limited period meaning that the patent owner alone is entitled to exploit and derive economic benefits from the invention. In return, the patentee has to agree to the publication of the invention. Thus, a patent can serve as a standard for other inventors and as a basis for further developments in the relevant field of technology.

Furthermore, information on existing patents plays an important role in business decision-making processes avoiding expensive and unnecessary duplication of R&D as well as the risk of infringing other patent rights. Public patent databases allow detailed information on already known inventions to be obtained. Patent information gives an overview on the state of the art and the latest developments in a technology field. It allows innovators in a technology field to be discovered by investigating who filed for a patent application or who invented what. In general the patent portfolio of a company showcases its innovative potential and economic capacity and is an important factor in the evaluation of companies.

[238] Own depiction, data from http://iri.jrc.ec.europa.eu/scoreboard.html, tables 1_3.xls, 1_7.xls, 28.06.2011

With the same information it is possible to find out which technological developments competitors are working on (as long as patents are applied for). Patent analysis may also reveal the level of cooperation and sharing of R&D results along a value chain, in the industry or in strategic partnerships, e.g. between car manufacturers and their component suppliers or within the 'Automotive Fuel Cell Cooperation'. It is possible to analyse R&D priorities within a technology field. [http://www.dpma.de/english/patent/index.html, 18.11.2008]

Within this work a patent analysis is carried out using the database and the search engine esp@cenet of the **European Patent Office (EPO)**. It includes more than M80 patent documents from all over the world. These documents are primarily patent applications, i.e. the first publication of new ideas which normally appear before companies present their products on the market, not granted patents. [http://www.epo.org, 21.11.2008] EPO uses the Cooperative Patent Classification (CPC). It is an extension of the International Patent Classification (IPC) and is jointly managed by EPO and the US Patent and Trademark Office (PTO). It is divided into nine sections: A-H and Y (see *Figure 6-8*).

A	Human Necessities
B	Performing Operations, Transporting
C	Chemistry, Metallurgy
D	Textiles; Paper
E	Fixed Constructions
F	Mechanical Engineering, Lighting, Heating, Weapons, Blasting
G	Physics
H	Electricity.

Figure 6-8: IPC system[239]

The sections are sub-divided into classes, sub-classes, groups and sub-groups.[240] The CPC-classification symbol is made up of a letter denoting an existing IPC class, followed by a number (two digits) denoting the IPC section level. Optionally, the classification can be followed by a sequence of a letter denoting the IPC subclass level, a number (one to three digits) denoting the IPC group level, a forward slash "/" and a number (one to three digits) denoting the IPC subgroup or full classification. Optionally, the classification can be followed by a CPC subgroup represented by a letter which can be followed by a digit and a letter.[241] For example, H01M8/24B2F stands for:

IPC class	IPC Section	IPC Subclass	IPC Group	IPC
H	01	M	8	/24
Electricity	Basic electric elements	Processes or means, e.g. batteries, for the direct conversion of chemical into electrical energy	Fuel cells; Manufacture thereof	Grouping of fuel cells into batteries

Subgroup	CPC subgroup		
/24B2F	B	2	F
Grouping of fuel cells into batteries	Comprising spaced diffusion electrodes or electrode layers with interposed electrolyte layer or electrolyte compartment	with solid or matrix-supported electrolyte	comprising framed electrodes or intermediary frame-like gaskets

The following general aspects have to be considered during the patent analysis:

- Patent information is suitable for measuring the **innovative capacity of a technology field**. It also provides valid conclusions on the expenditure for R&D. The deduction of information on the attractiveness of a technology from the patent-life-cycle is based on the

239 http://www.wipo.int/export/sites/www/classifications/ipc/en/guide/guide_ipc.pdf, 21.11.2008

240 Unfortunately, the CPC, formerly ECLA system is not properly maintained, e.g. out of 1,500 randomly chosen data sets containing the word "fuel cell" for the years 2006-2008 only four data sets (0.3%) did not contain an IPC number, but 547 (36.5%) no CPC/ECLA number. Therefore, all evaluation carried out within this work uses the IPC classification number, not the CPC/ECLA number. http://www.epo.org/searching/essentials/classification/cpc.html, 12.09.2013

241 http://ep.espacenet.com/help?topic=ecla&method=handleHelpTopic&locale=EN_ep, 30.11.2008

assumption that a constant and linear relationship exists between the R&D activities and the number of inventions achieved. It is presumed that for all, or a defined share of inventions, patents are applied. Furthermore, it is assumed that the R&D activity is linearly related to the attractiveness of a technology. [Haupt et.al. 2004, p. 5]

- Patents are an indicator for the **inventive activity, the effectiveness of R&D and the perceived value of the invention**, because to be awarded a patent requires not only the efforts of inventors to develop innovations, but also successfully shepherding a patent application through the application process by patent counsel. Thus, the granting of a patent is an indicator that efforts at innovation were successful and that an innovation had enough perceived value to justify the time and expense in procuring the patent. [Heslin et.al., 2014 (1), p. 1]
- In reality, the assumption that patent applications are made for a constant share of inventions is wrong. In general, for product inventions patents are rather applied than for process inventions. Furthermore, product and process innovations occur at different levels of the product-life-cycle. Product inventions are typically achieved earlier, followed later on by process inventions. Thus, the share of applied patents decreases when the technology reaches the later phases of the technology-life-cycle. [Haupt et.al. 2004, p. 5, 6]
- Classification under CPC takes time. According to EPO, an estimated 90% of the documents that have to be classified are allocated a classification within eight months following publication. In reality, a significant number of patent applications are published in the database only after 36 to 48 months, resulting in a gap between the actual number of patent applications and publication in the esp@cenet database during the classification period. In addition, there is a gap between the number of patents applied for and the number of patents granted. About 50% of the patent applications are successful; this share has increased during recent years. The esp@cenet database offers data on the number of patent applications, information on patents granted is not available in a format suitable for evaluation in a patent statistical analysis.[242]
- The total number of patent applications varies from year to year in response to the general economic situation, the availability of public and private funds for R&D activities or the innovation pressure in a specific technology field etc. In recent years, the number of patent applications rose on average by about 5% p.a. Nearly 20% of the total number of patents granted are accepted in the technology field of “Electrical engineering: Electrical machinery, apparatus, energy”.[243]

Within this work the following patent analysis has been done:

- A general patent statistical analysis covering the annual number of patents applied in relevant technology classification groups up to the year 2013. However, this analysis depicts real development only up to 2009/2010 because experience showed that patent applications were still being added to the database in a significant number 3 to 4 years following the application date.[244]

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242 The IPC-symbols assigned to the patent documents are linked to the technology field by a concordance. Because a patent application may be assigned multiple IPC-symbols, the sum of patent filings by fields of technology is higher than the total number of patent filings.

243 http://www.wipo.int/ipstats/en/statistics/pct/, http://www.ipyme.org/es-ES/publicaciones/Articulos/Documents/wipo_pat_appl_from_1883_table.xls, 12.09.2013

244 The search engine quotes the number of patent applications found for each query. This number is an approximation and is normally higher than the adjusted final result. During the first search run all single applications of a **patent family** are counted. Generally, a patent application for an invention is originally filed in one country. This original patent application may form the basis for filing patent applications in several other countries. Furthermore, each of these new patent applications can become the basis for filing subsequent patent applications resulting in many patents throughout the

- Detailed analysis of patents of key car manufacturers and producers of H_2FC-equipment including the investigation of co-operations between companies,
- Analysis of H_2FC-technology key research areas and a comparison between companies.

6.2.2.1 Patent statistical analysis of H_2FC technology

The Patent Statistical Analysis describes the level of R&D activities in a technology field by counting the number of patent applications and its development over time. The number of patent applications is also used as a parameter to determine the position of a technology in the technology-life-cycle, because logically the number of patents depicted in a patent-life cycle, antedates the level of technology dissemination (*Figure 6-9*). In theory, the number of patents applied for over time is depicted as a bell-shaped curve. The patent-life-cycle curve has the same shape as the technology-life-cycle, but the patent-life-cycle peaks earlier in time. The size of the peaks and the areas under the curves are not comparable due to different units used for the y-axis.

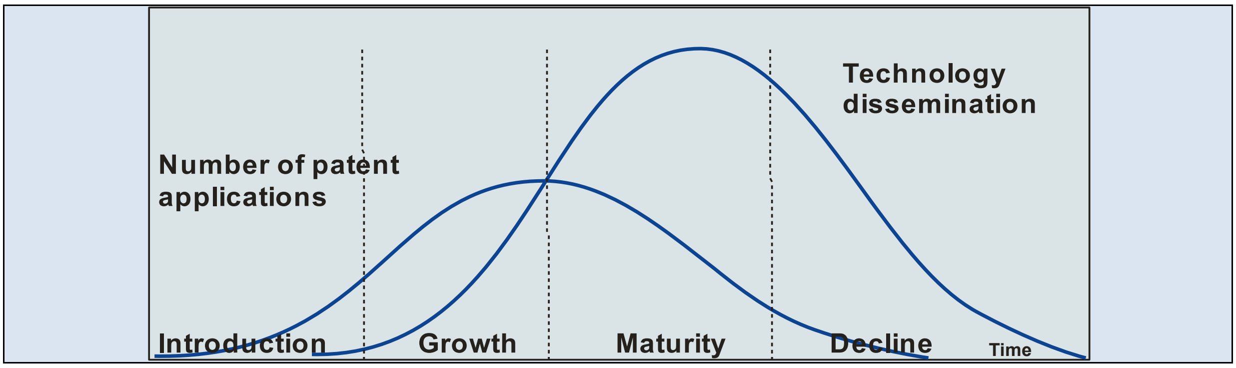


Figure 6-9: Relation between the technology life-cycle and patent numbers

FC-research looks back on a long history. FC technology development has its origin in the early 1950s with a first push of the technology in the 1960s. The PEMFC was invented at General Electrics in the early 1960s. The number of FC patent applications grew from five applications in 1960 to a temporary peak in 1969 when the total patent application number was 170. Due to the tremendous costs of FC-technology it was only available to niche markets like aerospace and military applications and R&D interest declined to a minimum in 1975 (38 applications). The 1970s saw a phase of low interest in FC-technology research. FCs regained interest at the end of the 1980s (first MCFCs). Since then the number of applications has grown more or less steadily for more than 30 years indicating the interest of various industries in this technology. The annual number of patent applications filed reached a maximum of 8,138 applications indicating a technological maturity in 2007. The overall num-

world. All patents and applications associated with the original patent application are called a patent family. According to the “Right of Priority”, as agreed in the “Paris Convention for the Protection of Industrial Property”, firstly signed in Paris on 20 March 1883, the patentee shall be able to use his first filing date (in one of the contracting State) as the effective filing date in another contracting State, provided that the applicant files another application within 6 months (for industrial designs and trademarks) or 12 months (for patents and utility models) from the first filing.

The exact number of original patents or inventions could only be obtained by scrolling through the whole list, because then only one patent document is displayed per patent family. This is not possible for long lists (more than 500 entrees). For the overall analysis, where large number of entrees occur, it is assumed that this deviation is systematically and occurs in all search queries in the same order of magnitude. In an analysis it was found that the reduction factor is about 70%, older patent lists are “boiled down” less, than new ones.

http://v3.espacenet.com/help?quickHelpPage=resultslistExtended.2&locale=en_EP&method=handleQuickHelp; 01.12.2009 ber of patent applications is - also in comparison to other ‘green’ technologies - huge, thus a tremendous financial R&D effort may be implied.

Figure 6-10 depicts the results of the statistical patent (application) analysis for a set of innovations. In comparison to other innovative technologies the very number of patent applications in the technology field “fuel cell” is notably greater and the innovation life-time is very long. For example, the mobile telephone technology came rapidly up by the end of the 1980s, but peaked already in 2006. Since then the technology has changed significantly several times and patent application numbers remain at a high level. LCD technology is another example of the course patent application numbers may run. The technology came up at the beginning of the 1980s and peaked in 2008. Since then, the number of patent applications has strongly declined. Solar energy technology has a comparable innovation time to FC-technology. First applications date back to 1961 and patent application numbers only started to climb significantly in 2009. In 2011, the number of patent applications was higher than for FC-technology for the first time. The shape of the application curve points to an even stronger increase within the years to come. This is confirmed by the patent granting numbers recently published by the US patent office (Figure 6-11).

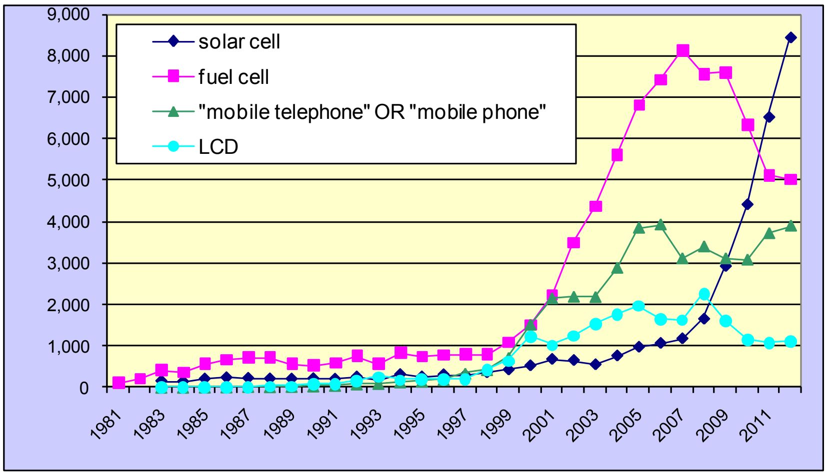


Figure 6-10: Statistical patent analysis of various innovations[245]

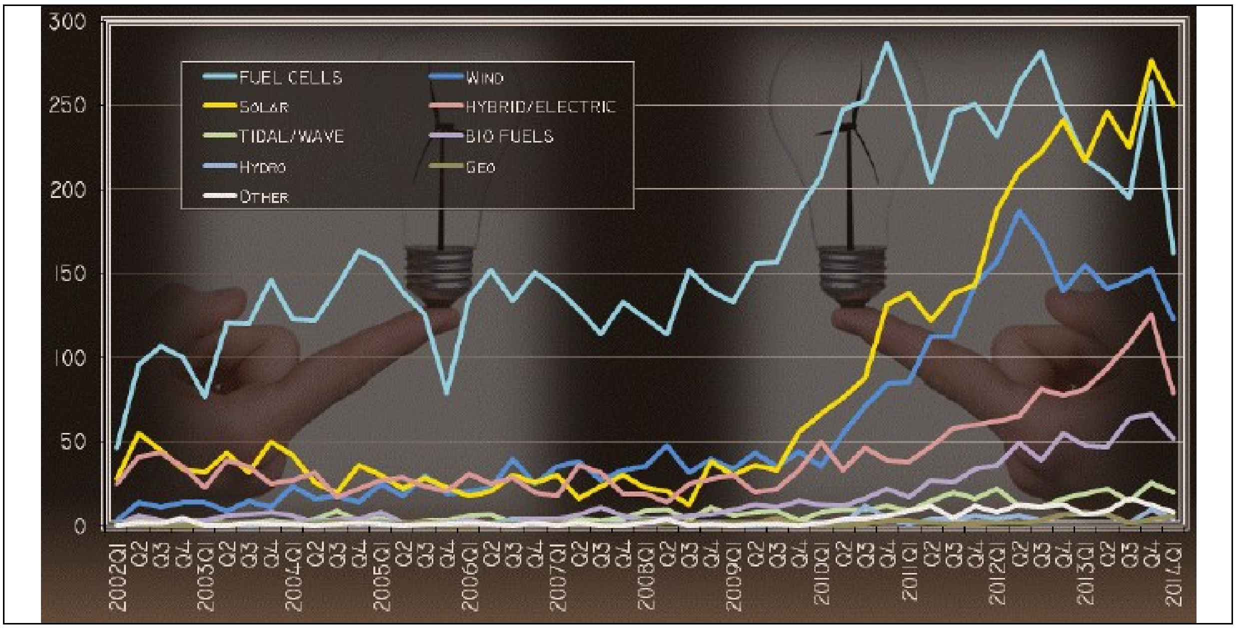


Figure 6-11: Sector patents granted by US Patent and Trademark Office, 2002-2014 [Heslin et.al, 2014 (2), p. 1]

245 This analysis searched for the named key words in the title and simply counted the number of patent applications per year. Due to the large figures, a reduction of patent applications within a patent family to one entry could not be realised, please refer to footnote 244.

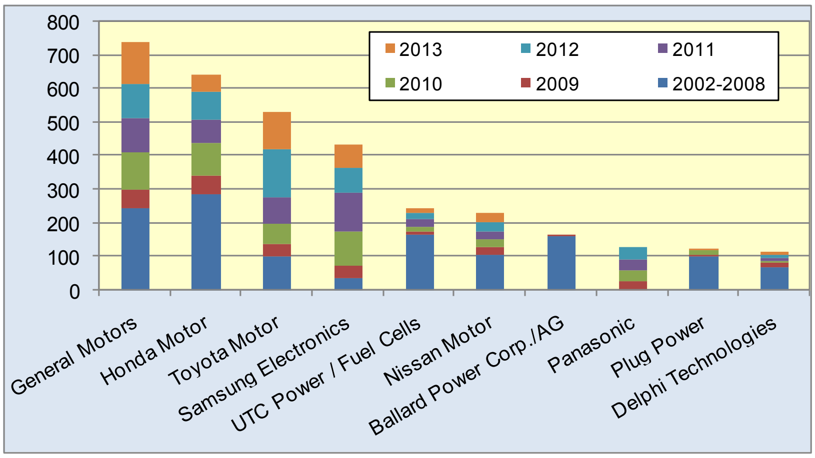


Figure 6-12: Top 10 FC energy patent assignees 2002-2013 [Heslin et.al, 2014 (1), p. 6]

The Clean Energy Patent Growth Index (CEPG) publishes quarterly the granting of US patents from the renewable energy sector. In 2012, clean energy technology patents were at an all time high of 3,061 or more than 30% over 2011. Only in 2013, was the FC-sector (886 patents) toppled by Solar technology (965 patents), after being in the leading position since 2002. GM (total since 2002: 912; in 2013: 128 FC, 31 hybrids) collected the most clean energy patents, followed by Honda (total since 2002: 863; in 2013: 52 FC, 31 hybrids). Toyota (total: 769; in 2013: 110 FC, 46 hybrids) moved into third place. Toyota reached its position through regular patent granting for hybrid technology and recently strong activities in FC-technology. Four of the top ten 2013 FC clean energy patent holders are auto manufacturers with the other six including an assortment of wind, solar and FC-makers such as UTC and Ballard. Ballard was barely able to hang on in the top ten with no additional contribution since 2009. The **CEPG FC breakdown** shows that GM (742) remained ahead of Honda (642) and Toyota (530), see *Figure 6-12*. *Figure 6-14* depicts an analysis of the EPO patent applications of the most important FC-producers (all use), the car industry is analysed separately (see *Figure 6-13*).

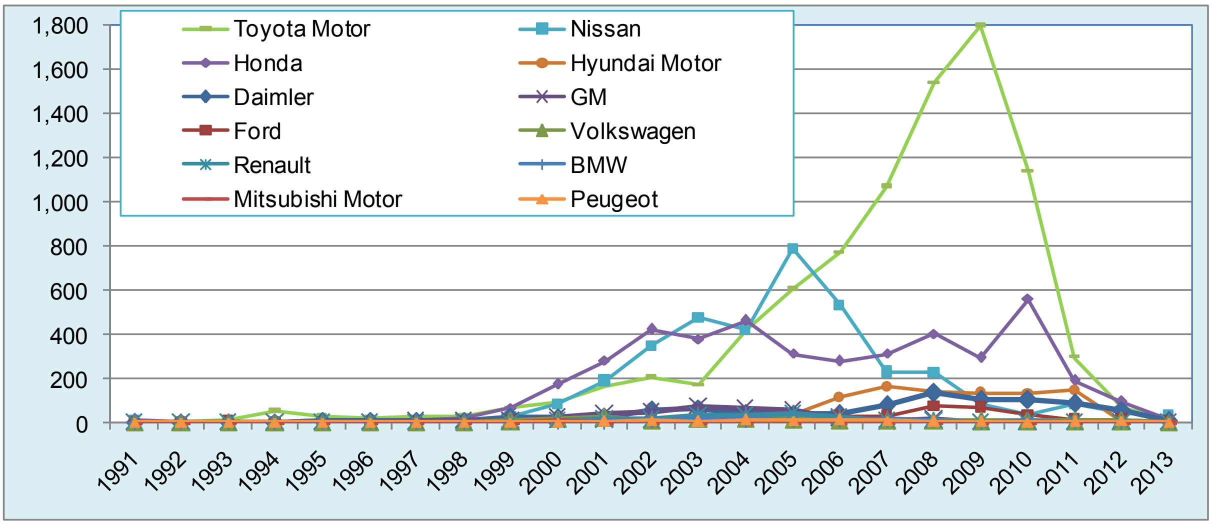


Figure 6-13: Annual number of EPO patent applications of the main vehicle manufacturers (keyword in topic and summary "fuel cell")[246]

[246] The search engine esp@cenet allows downloading a maximum of only 500 data sets per query. The query could be narrowed by the company name, one or more key words and the year of publication. In the cases of Toyota Motor Company, Nissan Motor Company and Honda not all data sets could be downloaded for every year. When the number of data sets found using the query "year of publication, e.g. 2008, fuel cell and Toyota Motor" exceeded 500 after the data condensation the total number of applied patents was estimated. The condensation factor was applied to the remaining, not downloaded, data sets. The publication year was used for the uncompleted search runs.

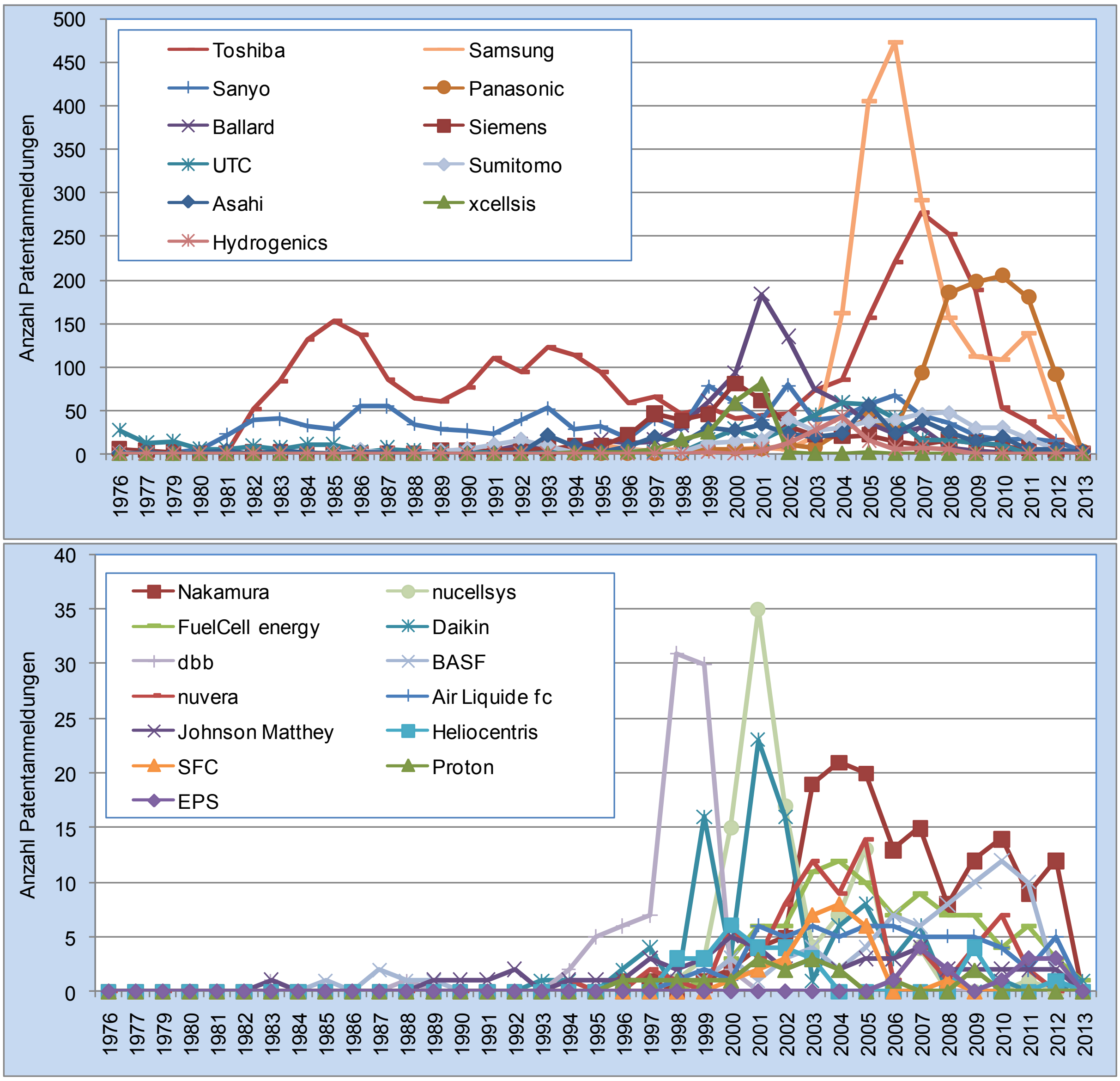


Figure 6-14: Number of applied EPO patents of FC manufacturers, key word: fuel cell[247]

The FC research activities at the FC-producers already peaked, e.g. Ballard and Siemens in 2001, UTC in 2005. In any case, the number of patents is quite low, even Ballard, the leader in this technology field, holds only 806 patent applications, not including the applications of xcellsis (193) and nucellsys (101). Thus, the majority of the patent applications does not lie in the hands of the classical FC-producers. Ballard naturally cooperated with the members of the AFCC. In addition, 1% of the applications were applied for together with Johnson Matthey. Siemens applied for 7% of its patents together with Emitec Emissionstechnologie, a

247 The search includes **all** condensed patent applications of the specified FC-companies. For large companies, busy in more than one technology field, the selection was limited to e.g. “Siemens” AND “fuel cell”. The analysis and all illustrations are using the application date, because the publication date depends on the work load at EPO. (In the rare case of a missing application date, the publication date was used for analysis (it is not possible to search for the application date).) The time gap between patent application and publication is an average of sixteen months, maxima up to two years also occur. All patent applications registered under the company name are counted independently of the location of the branch, e.g. the data for xcellsis include German, US and Canadian patent applications.
Duplicate applications were eliminated from all companies (2% of data sets).
United Technologies outsourced its FC business, incl. the research activities, to its subsidiary UTC FC. Since 1995 all patents were registered at UTC FC (except for three patent applications in 2005).
The Air Liquide subsidiary Axane does not apply for its patents under its own name.

German supplier of automotive catalysts. Big electronic companies such as Samsung, Sanyo or Toshiba hold the most patent applications. For Samsung, Sanyo and Toshiba there are no relevant cooperation partners apparent from the application data.

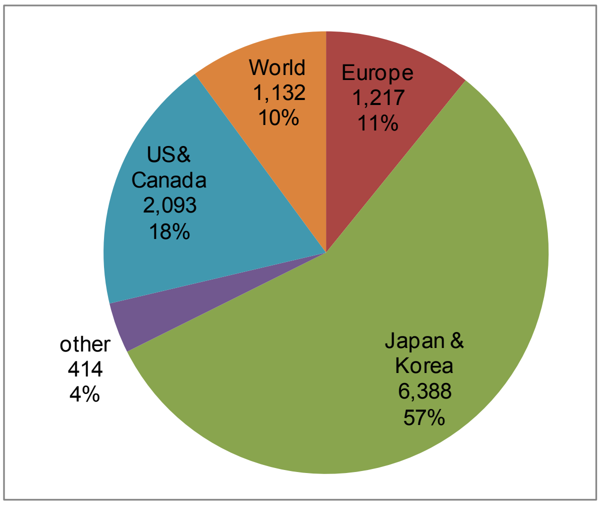


Figure 6-15: FC technology applications by location of patent application

The origin of the patentees displays the often denounced weakness of the European FC-industry. Only 11% of the patents were applied for by companies with headquarters in Europe. 18% are located in the US or Canada and the majority in Japan or Korea (57%), see *Figure 6-15*. This weakness is more high-lighted when looking at the individual inventor. His/her nationality gives a hint as to the real location of the invention. In the cases where both data were available (40% of data), a comparison was carried out. 90% of the patents applied for in Japan or Korea were from local inventors; the share of US local inventors was just 16%. This discrepancy is due to the fact that, for example, almost all inventions from the German Adam Opel AG are applied for under the US General Motors. In contrast, Ballard, one of the most important mobile FC-technology developers, is majority-owned by the German company Daimler. Many H_2FC-technology related patents are in the hands of the vehicle manufacturers (see *Figure 6-13*).

Company	Partners
Toyota Motor[248]	81.8%
Toyota, others[249]	7.3%
Toyota, Aisin	4.9%
Toyota, Nippon Soken	1.5%
Toyota, Institute&Univ.	0.6%
Toyota, Matsushita	0.6%
Toyota, Nisshin Steel	0.6%
Toyota, Sumitomo	0.5%
Toyota, Cataler	0.5%
Toyota, Denso	0.4%

The three Japanese companies Toyota, Honda and Nissan registered the most patent applications. Up to 2008/09 there was no clear peak visible for automotive FC-R&D activities according to the patent application numbers. The main cooperation partners of the car manufacturers were assessed. The analysis is mainly based on data up to 2008, but a short check showed that the analysis is still valid. **Toyota Motor** holds about 8,570 FC-applications[250] at EPO. Toyota Motor, or its affiliated companies, only seldom enters into a partnership (18%). Some of the rare partners are Aisin Seiki (5.3%), Nippon Soken (1.6%, measurement and analysis technology [http://www.nipponso-ken.com), institutes and universities (0.6%), Cataler (0.5%, catalyst producer, [http://www.-cataler.co.jp]) and Sumitomo's (0.5%, steel and non-ferrous metals, transportation systems, development of materials, electronics, batteries etc. [www.sumitomocorp.co.jp/en]) Toyota holds patents for a wide range of FC products and manufacturing processes, such as FC parts, systems and their integration, catalysts, reforming technologies as well as methods of manufacturing membranes and electrodes, e.g. hydrogen occlusion alloy electrodes and their assembly. There is no increase in the share of processing and manufacturing patent applications identifiable.

248 Including affiliated companies such as Toyota Central Research & Development and Toyoda Automatic Loom Works (Toyota Motor was spun out of this company in 1937)

249 Others are mainly patent applications filed in corporation with private persons, e.g. employees.

250 The esp@cenet lists only patent applications and publications. It is assumed that the share of rejected patent applications is the same for all companies analysed.

Honda holds the second rank of EPO FC patent applications (4,300). It is also mainly working on its own. The number of patent applications forms a much longer plateau than that of the other manufacturers. Cooperation partners are Japanese JSR Corporation (1.6%) specialised in petrochemical materials and polymer technologies. [http://www.-jsr.co.jp/jsr_e/company/index.shtml] Symyx Technologies (0.7%) is a US contract research company with a key qualification in combinatorial chemistry applied to heterogeneous and homogeneous catalysis. [http://www.symyx.com] Japanese JMC produces ferroalloys, high-purity metals, hydrogen-occlusion alloys.[251]

Company	Partners
Honda	86.2%
Honda, others	10.5%
Honda, JSR	1.6%
Honda, Instit.&Univ./ others	0.6%
Honda, Symyx/others	0.7%
Honda, Japan Metals & Chemicals	0.4%

Nissan applied for the third largest number of FC-technology patents (3,122). Nissan's application volume peaked already in 2005. Nissan's main co-operation partners are UK based Calsonic Kansei (0.3%), Japanese Hitachi (0.2%), French Renault (0.2%) and US UTC (0.1%). Nissan owns 41.8% of Calsonic Kansei which specialises in the design and manufacture of heating and air conditioning systems, engine cooling and exhaust systems, including catalytic converters. There are no joint patent applications between Daimler or Ford and Nissan, although these three companies signed a cooperation agreement in 2013. Renault holds a 43.4% stake in Nissan, while Nissan holds 15% of Renault shares. Nissan and Renault pool their expertise and co-operate on engineering, production and distribution. The Renault-Nissan Purchasing Organisation covers Renault's and Nissan's purchases. The alliance adopted a policy of interchangeable components.[252] Renault and Nissan pool their R&D resources, among others, in the area of FCVs and HEVs.

Company	Partners
Nissan	92.0%
Nissan, others	6.1%
Nissan, Institute&Univ.	1.2%
Nissan, CalsonicKansei	0.3%
Nissan, Hitachi	0.2%
Nissan, Renault	0.2%
Nissan, UTC	0.1%

Figure 6-16 shows the number of patent applications without the "Big Three" Japanese companies Toyota, Honda and Nissan. Korean Hyundai has increased FC-patent application numbers significantly since 2005. Daimler and Ford are both members of the AFCC and have partly "outsourced" their FC R&D to Ballard, Nucellsys etc. GM lost its leading position during the financial crisis and only holds a minor role today. Opel carries only five patent applications. French Renault and Peugeot only play a subordinated role. The Italian Fiat Group has not applied for any patent in the fields of FC-technology, but Centro Ricerche Fiat (CRF), an engineering affiliate holds at least some applications. In 2005, Fiat signed a co-operation agreement with Nuvera on FC-development and delivery. In September 2007, CRF provided three FC Pandas for the city of Mantua within the European "Zero Regio"-project. [http://www.italiaspeed.com/2005/cars/other/technology/12/nuvera/0612.html, 22.05.2009]

Korean **Hyundai** applied for 1,030 patent applications, mainly on its own. The rare participation of private persons is noticeable. Since 1998, Kia Motors has belonged to Hyundai Motor. R&D cooperation with Kia on FC-technology has recently increased (based on 2013 data).

Company	Partners
Hyundai	75%
Hyundai, Kia	19%
Hyundai, Instit.&Univ.	4%
Hyundai, others	2%

[251] http://www.jmc.co.jp/jmc.nsf/doc/english_index
[252] http://www.renault.com/en/groupe/l-alliance-renault-nissan/pages/fonctionnement-et-structure.aspx

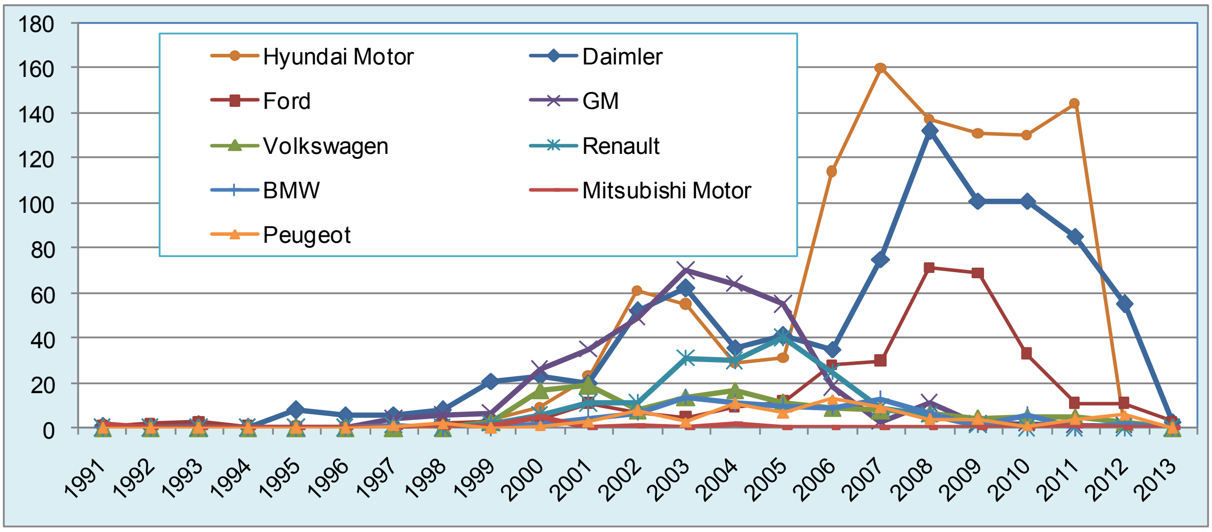


Figure 6-16: Annual number of patent applications using the keywords “fuel cell” of the main vehicle manufacturers (without “Big Three”: Toyota, Nissan and Honda)

Company	Partners
Daimler	70%
Daimler, others	14%
Daimler, Ford, Ballard	12%
Daimler, Aerospace	2%
Daimler, Steyr	1%

Daimler applied for 880 patents, mainly on its own or in co-operation with the AFCC and its precursors. In addition, Daimler has access to the technology of its subsidiaries xcellsis, dbb (closed down) and NuCellSys (91 applications). Until 2000 the Deutsche Aerospace AG (founded in 1989) was also a subsidiary of Daimler-Benz. Magna Steyr designs, develops and manufactures automotive systems, assembles modules, components and complete vehicles.

Company	Partners
GM	74%
GM, others	24%
GM, Opel	1%
GM, Institute & Univ.	1%

General Motors’ number of applications (total 372) peaked already by 2003. GM mainly acts on its own resources when developing FC-technology. In European projects, test vehicles by Adam Opel AG are often used, but the related patents are mainly applied for under the umbrella of GM.

Ford applied for 340 patents, mainly on its own or in co-operation with the AFCC. The technology dependence on the AFCC (2013: 57%, 2008: 31%) is much higher than for Daimler. All patents are applied for via the US branch, e.g. there are no patent applications by the Ford Forschungszentrum, Aachen. In 2002, Ford Global Technologies, LLC, Dearborn, Michigan was incorporated. It owns, manages and commercialises patents and copyrights for Ford Motors and applied for 63% of Ford’s FC-patents.

Company	Partners
Ford	39%
Ford, Daimler /others	57%
Ford, others	4%

Company	Partners
Renault	72%
Renault, others	23%
Renault, Nissan	3%
Renault, PSA	2%

Renault applied for 175 patent applications, mainly on its own. In some projects Renault co-operated with Nissan with whom it has a general co-operation agreement. On a limited scale there are also co-operations with other French vehicle manufacturers such as PSA.

Company	Partners
BMW	71%
BMW, others	20%
BMW, DLR, others	6%
BMW, Delphi, others	3%

BMW applied for 87 patents, mainly on its own. In contrast to the others, BMW focused on the development of H_2ICE technology in the past. It co-operated with the German Aerospace Centre (DLR) and Delphi.

The **automotive component suppliers** play a minor role in FC technology development. This is supported by the limited total number of FC patent applications from this group. When analysing the number of patent applications in the field **B60L11/18**[253] the vehicle manufacturers are clearly in the majority, i.e. Delphi holds 7 and Bosch 5 applications. A closer analysis of the patent applications of the automotive suppliers shows that, once again, the leaders are Japanese companies: Aisin Seikin and Denso followed by Bosch and US Delphi (see *Figure 6-18*). Not surprisingly, the suppliers applied for patents in very specific technology fields such as electrodes. Notably, only Bosch has applied for FC system integration patents to date.

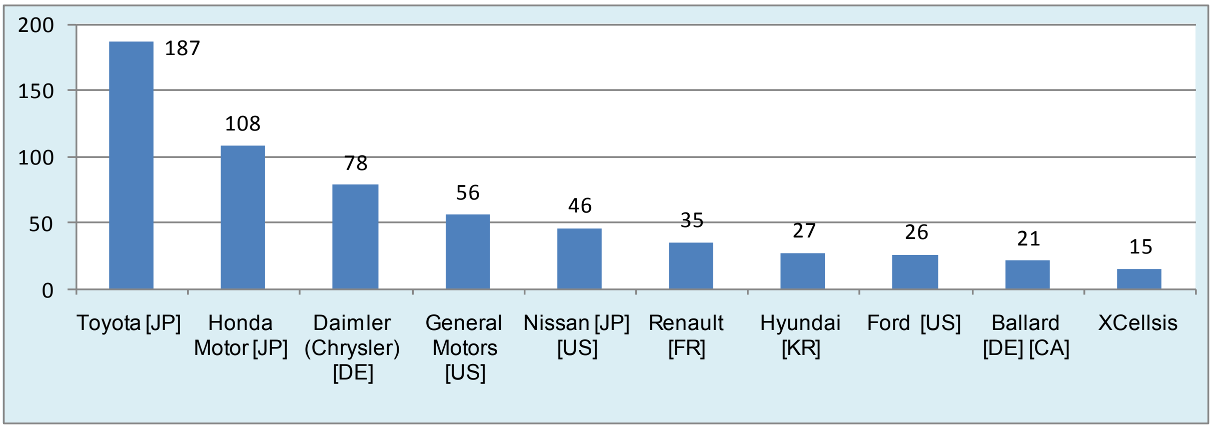


Figure 6-17: Main applicants for patent of sub-group B60L11/18

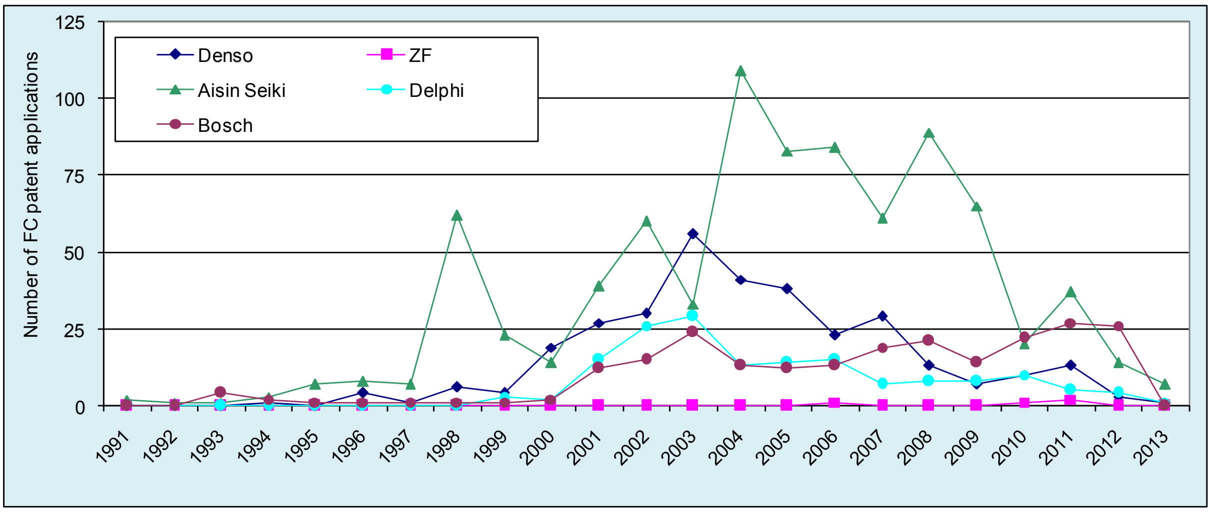


Figure 6-18: Annual number of patent applications using the keyword "fuel cell" of the main automotive component suppliers

Other important industrial sectors for the development of H_2FCV-technologies are the gas producers and the mineral oil companies. The **gas industry** has had an increased interest in H_2-technology since the end of the 1970s. Since 1999, research in the production of H_2-fuel has increased. In particular, Air Liquide has strongly expanded its activities, see *Figure 6-19*.

The mineral oil companies have vast experience in the handling of hydrogen from their mineral oil processing activities. However, they applied only for a handful of H_2-fuel handling related patents. This clearly indicates the role allocation: the mineral oil industry will operate

253 Performing operations; transporting / Vehicles in general / Electric equipment or propulsion of electrically-propelled vehicles; magnetic suspension or levitation for vehicles; electrodynamic brake systems for vehicles, in general / Electric propulsion with power supplied within the vehicle using power supplied from primary cells, secondary cells or fuel cells

the filling stations and sell the hydrogen, but the transmission and distribution technology will be provided by the gas industry.

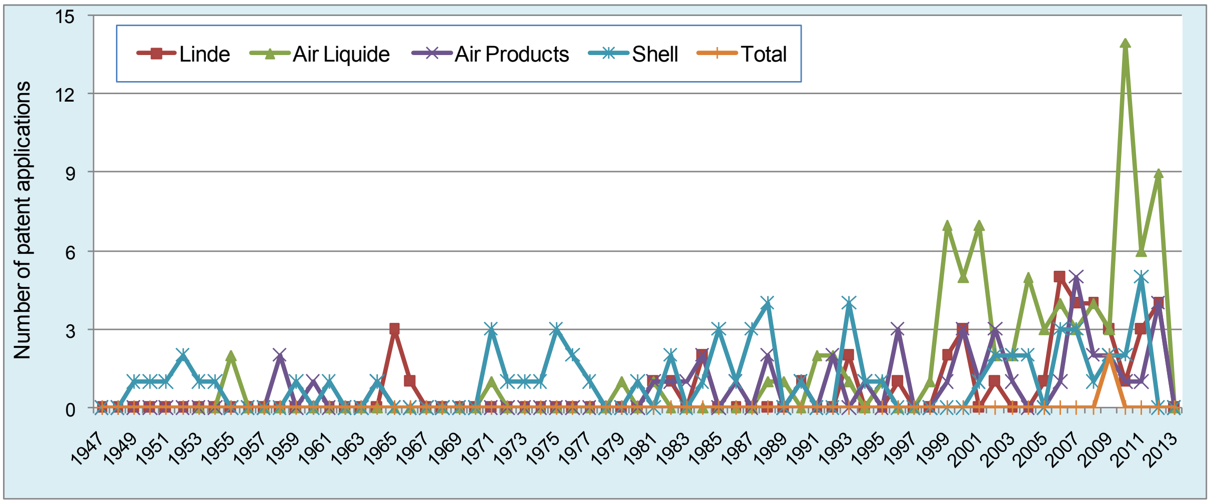


Figure 6-19: Annual number of patent applications of the main gas and mineral oil companies, selection "hydrogen", "production"

In a last step, the patent application number of different FC- and supporting technologies were analysed (see *Figure 6-20,* please note, the years 2011-2013 are underrepresented in the patent application database).[254]

Application numbers in **Subgroup H01M8/00** (manufacture of FCs in general) have increased since the beginning of the millennium. **Subgroup H01M8/08** specifies the manufacture of FCs with aqueous electrolytes, i.e. Alkaline Fuel Cells (AFC). AFCs are one of the earliest used and most developed FC-technologies. They have been widely used to produce electrical energy and water on-board spacecrafts by NASA in the Apollo and Space Shuttle programs since the mid-1960s. A first patent publication dates back to 1952. Patent applications first peaked in 1966 (44 applications) and secondly in 1986 (41 applications). After 2000, the technology gained interest again and denoted a longer plateau of about 18 applications p.a. Since 2007 application numbers have been decreasing.

Subgroup **H01M8/10** describes the manufacture of FCs with a wide spectrum of solid electrolytes, i.e. SOFCs, PEMFCs and Direct Methanol FCs (DMFCs). Zinc-Air FCs are also covered, but only have minor importance today. General Electric and Siemens have been pioneers in the research of **SOFCs** since the late 1950s. Interest in the technology resurged at the millennium and since then patent application numbers have strongly increased.

[254] **B60K1/04**: Arrangement or mounting of electrical propulsion units of the electric storage means for propulsion
B60K15/07: Arrangement in connection with fuel supply of combustion engines; Mounting or construction of fuel tanks of gas tanks
B60L11/18: Electric propulsion with power supplied within the vehicle using power supplied from primary cells, secondary cells, or fuel cells
C01B3/02: Hydrogen; Gaseous mixtures containing hydrogen; Separation of hydrogen from mixtures containing it / Production of hydrogen or of gaseous mixtures containing hydrogen
F17C1/00: Pressure vessels, e.g. gas cylinder, gas tank, replaceable cartridge
F17C3/08: Vessels not under pressure by vacuum spaces, e.g. Dewar flask
H01M8/00: Manufacture of fuel cells
H01M8/08: Manufacture of fuel cells with aqueous electrolytes
H01M8/10: Manufacture of fuel cells with solid electrolytes
H01M8/12: Manufacture of fuel cells with solid electrolytes operating at high temperature, e.g. with stabilised ZrO_2 electrolyte
http://www.wipo.int/classifications/ipc/en/; 19.04.2009

PEMFCs were first used in the NASA Gemini program in the 1960s. Today, they are mainly developed to be used as a vehicular power source to replace the ICE. **DMFCs** were initially developed in the early 1990s, but were not embraced because of their low efficiency and power density as well as other problems. The technology behind DMFCs improved, but is roughly 3-4 years behind that for other FC-types. DMFCs were successfully demonstrated powering mobile phones and laptops.[255] Application numbers still have not peaked. Solid electrolyte FC patent applications are still at a high level of about 100 applications p.a.

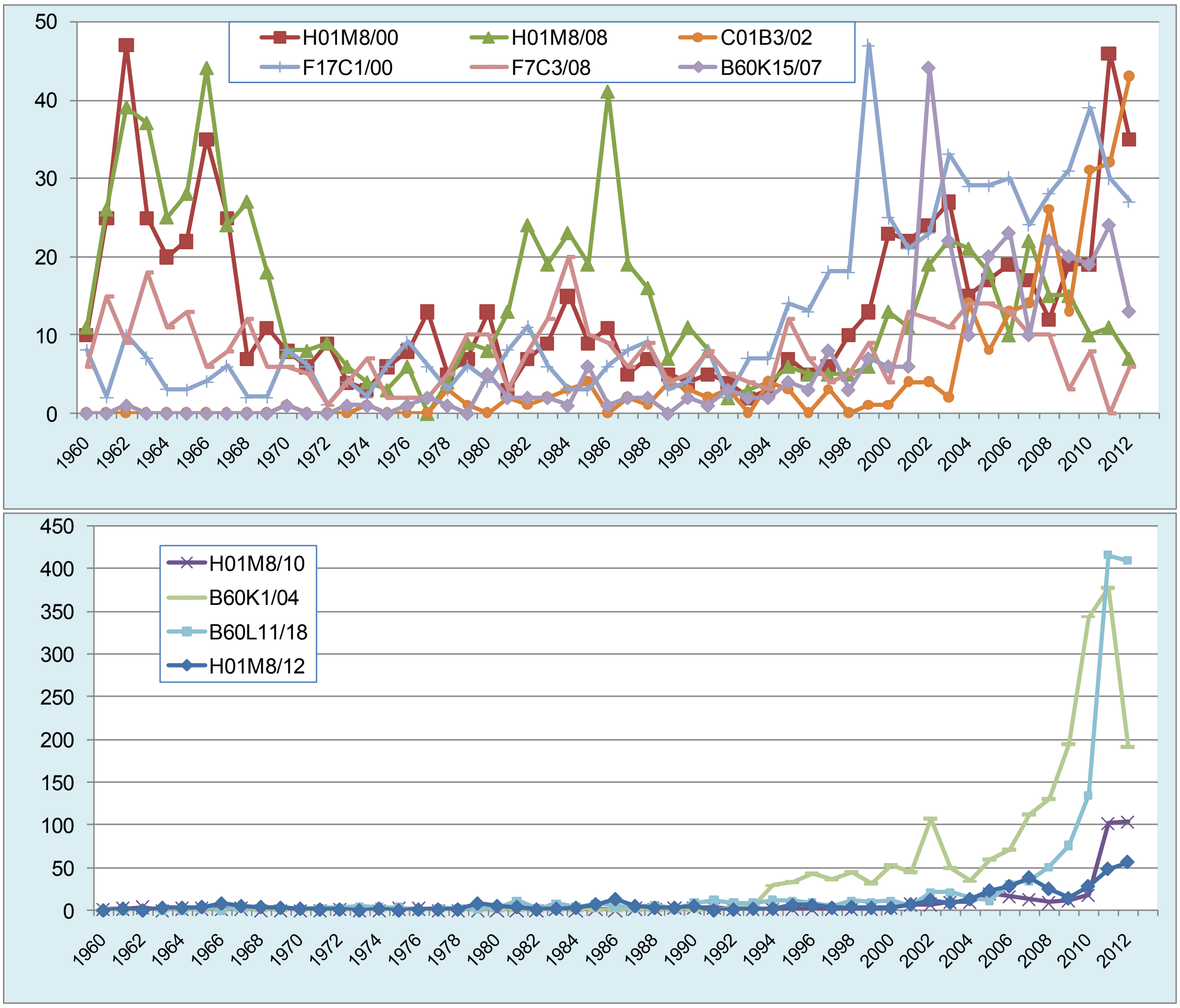


Figure 6-20: Patent applications for different FC- and electric propulsion technologies

Subgroup H01M8/12 refers to **Molten Carbonate Fuel Cells.** The very first patent applications were in 1953/1954. Since the 1960s they have undergone improvements in fabrication methods, performance and endurance and are currently more intensively developed for natural gas and coal-based power plants.[256]

In particular, patent application levels in the area of mounting of **electrical propulsions system units** (**B60K1/04**) (close to 400 applications p.a.) are still increasing strongly. Applications for propulsion systems from primary, secondary and fuel cells (**B60L11/18**) have increased since 2011 with more than 400 applications p.a., too (see *Figure 6-20*).

The IPC class including the mounting or construction of **gaseous fuel tanks** (**B60K15/07**) has had a constant application number (about 20 p.a.) since 2002. Under storing of gases in

255 http://energy.gov/eere/fuelcells/types-fuel-cells,22.03.2014
256 http://energy.gov/eere/fuelcells/types-fuel-cells, 22.03.2014

pressure vessels (**F17C1/100**) a comparable plateau of about 25 applications p.a. has been observed since 1997. Applications are mainly from private persons, specialist companies, but also from gas companies (AirLiquide etc.) and, occasionally, some vehicle manufacturers. **F17C3/08** “Vessels not under pressure by vacuum spaces”, i.e. suitable for the storage of LH_2, peaked already between 2001 and 2006 (13 applications p.a.).

C01B3/02 including the **H_2-production** has shown a continuous increase in patent application numbers since 2004, currently about 40 applications p.a.

In conclusion, at EPO FC related patents are mainly applied for by Korean and Japanese companies. The main applicants are Samsung (peak at 473 in 2006), Toshiba (peak at 277 in 2007), Panasonic (peak at 204 in 2010). For comparison, Ballard peaked at 183 applications already by 2001 and Siemens at 81 applications in 2000. The picture at the vehicle manufacturer is quite similar: applications including “fuel cell” peaked at Toyota with more than 1,700 applications in 2009, at Nissan with 783 in 2007, at Honda (probably) with 558 in 2010, at Hyundai with 160 in 2007 and at Daimler with 132 in 2008. For comparison, GM’s numbers peaked with 70 applications in 2003 and VW’s with 19 in 2001. Even if the Asian companies have a different attitude towards patent applications, the strength of Toyota, Honda, Samsung and Panasonic is confirmed by the patents granted from US PTO. GM seems to be a particular case: GM received the most US patents during recent years, but applied only for very few patents in Europe.

FCV related R&D has been pursued by the major car manufacturers for about 25 years. In the 1990s, FC stack development was concentrated at companies such as Ballard, UTC or Hydrogenics. Car manufacturers concentrated on system integration. Only after 2000 did car manufacturers incorporate most FC-stack R&D within their own companies. In the meantime, the automotive companies have developed their own FC-stack and systems, acknowledging the important role in the value chain of the future vehicle, but still purchasing stack components from external suppliers. They are partnering up for specialised components with dedicated companies, e.g. for catalysts and polymers. Importantly for the market introduction of FCVs, also related technologies such as storage containers and H_2-production as well as electric propulsion system and energy management systems became relevant R&D topics, but have not yet peaked. The availability of these technologies is a prerequisite to the reliable operation of FCVs and for decreasing FCV-system costs. Patent applications on FC system production processes are rare since they are often not patented.

However, a cost reduction for H_2-fuel also has to be achieved, but the mineral oil companies are not active at the moment, but the gas companies have applied for some patents. In addition, the number of applications for electrolysers has increased since 2007 (about 25 p.a.).

6.2.2.2 Patent statistical analysis of NGV technology

NGV-technology had a head start over H_2FC-technology. Thus, experience from the marketing process of NGVs could be analysed to derive information on the progress of H_2FC technology market development. The NGV market is far more developed than the FCV market in Germany. NGVs managed to enter the early growth phase of market development during the last decade. Several attractive NGV models are currently being launched.

Figure 6-21 depicts the relationship between the number of NGV EPO patent applications and NGV registration numbers in Germany. The NGV market is split between an OEM and a retrofit market. The number of patent applications was analysed according to different countries of patent origin. Only patent applications from countries without a conversion market were taken into account, assuming that this kind of technology is used in the vehicles registered in Germany.

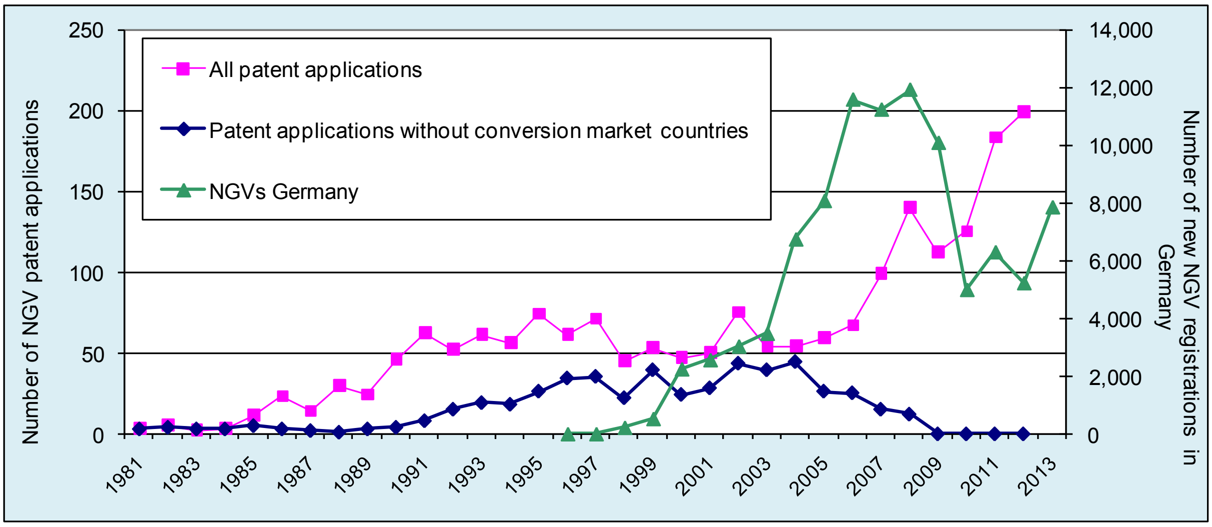


Figure 6-21: CNG patent applications in comparison to NGV registration numbers

Interest in NGV-technology R&D increased in 1990 (non-conversion market). By 1995 the number of patent applications reached a low level plateau which remained steady for about ten years (33 patent applications p.a.). The patent level was quite low, which shows that NGV-technology is comparatively simple and/or that the market has been evaluated as not very attractive. The engine uses the well-known Otto-technology with some adaptations due to the different fuel combustion characteristics (higher pressure and temperature). The infrastructure takes advantage of the existing natural gas distribution network and the mature compressor and storage technology. The main R&D challenges are the provision of light, safe, on-board vehicle storage bottles which do not require too much payload and space (packaging problem) as well as the optimisation of the engine technology. It took approximately twelve years between the notable increase of NGV patent publications in 1991 and the rise of NGV registration numbers in 2002/2003. Since 2005, the number of patent applications has declined significantly; since 2009 there have been no applications in the non-conversion markets. Thus, the main R&D phase lasted about twenty years. The NGV market achieved a small growth phase only after the main R&D phase was completed, approximately in 2007/2008. The relationship between patent applications without conversion markets and the number of NGV-registrations in Germany resembles the theoretical relationship between the number of patent applications and product success in the market (*Figure 6-9*).

The lessons learned for FCV market development from NGV patent analysis is twofold. FCV-technology is far more complex than the NGV-technology and the market potential is much larger. This is reflected in the larger number of FCV patent applications. FCV-development benefits from NGV's onboard storage and gaseous fuelling technology research results. However, the infrastructure requirements for the H_2-economy are much more difficult to be met because hydrogen, in contrast to natural gas, is not yet a widely distributed fuel. In addition, if the results from the market development of NGVs could be transferred, then one may reckon with a considerable increase in FCVs registrations only after completion of the main R&D phase. The time gap is about 8 to 10 years. The patent analysis has shown that H_2FC-technology is just entering the decline phase of patent applications. According to the literature analysis major FCV-manufacturers announce the start of technology dissemination for a period between 2015 and 2020. This timing complies with the theoretical patent application / technology dissemination cycle which was confirmed by the findings of the respective NGV-cycle. Notable, even if there are now many CNG models available and NGVs, from the TCO point of view could replace most petrol vehicles in Germany [Plötz, 2013, p. 7], they are simply not being bought by the customer.

6.3 Analysis of future H_2FCV market development - Delphi-Analysis

The Delphi-Analysis is named after the ancient oracle in Delphi, the seat of the most important ancient Greek temple and the oracle of Apollo, the son of Zeus; among others the God of truth and prophecy. In ancient times, oracles were a medium for divine communication and delivered in response to a petitioner's request, e.g. a forecast on the outcome of projected wars or political actions. [Encyclopaedia Britannica, 1994, Vol. 3, p. 979; Vol. 8, p. 974] In modern times, the Delphi-Analysis was first developed by Norman Dalkey at the RAND Corporation for military purposes to project possible strategic targets of Soviet missiles in the USA in the 1950s. [Hsu, et.al., 2007, p. 1] Since then, it has been used and adapted to address a variety of complex future-oriented questions, e.g. long-term projection of scientific and technical developments (first 1964).

Today, the Delphi-Analysis is a method for knowledge capture and consensus building. It is characterised by the anonymity of the experts questioned, iteration, controlled feedback and statistical response. It is widely used and accepted in a variety of social, managerial and technological areas. The Delphi-Analysis deals with a controlled prognosis of the future, enables a comparison of alternative drafts of the future and allows a consensus between experts to be reached. Four general types of Delphi-Analysis emerged:

- **Type 1: Delphi-Analysis to aggregate ideas**: This is an exclusively qualitative assessment on existing and new ideas which are collected from the expert panel during a first round. The results are reported back to the expert panel. In the second round, new assessments are collected. The target is to gain a high number of different ideas for solving a problem. The expert panel has only a few participants from different disciplines.
- **Type 2: Delphi-Analysis for forecasting unknown circumstances as exactly as possible**: This could be a quantitative or qualitative assessment. The problem has to be described exactly. It is used to determine one right future value, e.g. price prognosis for fruits. A number of specialised experts are selected.
- **Type 3: Delphi-Analysis for investigating and qualifying the opinion of an expert panel on an unknown problem**: This is the most often used type of Delphi-Analysis, today. It may be a qualitative, but is mostly a quantitative assessment. The problem has to be described exactly in a questionnaire. The results are used to draw conclusions about necessary interventions to react to the problem investigated or measures to positively influence a development or to detect erroneous trends. The target is not to determine the future, but to discuss the future and possibilities for its active shaping, e.g. a Delphi-Analysis on the Future of Science and Technology (German Ministry for Research and Technology, 1998).
- **Type 4: Delphi-Analysis to create a consensus between participants:** This is normally a quantitative assessment. The Delphi-analysis is used to prepare, for example, for a democratic decision finding. [Häder, 2002, p. 26-36, 103]

The Delphi-Analysis has many advocates, but some reviewers of the methodology criticise it for:

- the process not being well structured and the composition of the expert panel not well defined (no clear selection criteria),

- the fact that even highly acknowledged experts are often not able to give correct statements on future developments in their field of expertise,
- the high adaptability of the methodology to a wide range of applications indicating that the methodology is badly defined and only insufficiently scientifically secured,
- the fact that the two targets of a Delphi-Analysis create, on the one hand, a consensus between the participants and, on the other hand, solve a problem are contra dictionary, because real experts are known to defend an opinion independent of a group opinion,
- the thesis is wrong, that 1+n people aggregate at least the same, but probably more information than one person, because with a growing number of participant the impact of bad information also grows.

However, despite these weaknesses there is a large consent that the methodology has the potential to contribute to a decision-finding process as well as to the elaboration of projections on complex innovative topics. For a successful Delphi-Analysis, it is necessary to clearly define its targets and to orientate the procedure according to these targets. In addition, through the feedback process, which uses statistical means like mean and median, the group judgement may be compared with individual judgements. If the individual judgements follow a Gaussian distribution, the group judgement should deliver a good result. Furthermore, the debate, as to whether a Delphi-Analysis can deliver the one right value is superfluous, because most types of Delphi-Analysis are not even interested in this “right value”, but in learning about the opinion of the expert panel. [Häder, 2002, p. 26-27, 36-41] This is also the case for the thesis work at hand. For the purpose of this thesis the Delphi-analysis is viewed as the most suitable tool for collecting expert opinions on the subject of ‘marketing hydrogen as a fuel’, because:

- The problem of market introduction of hydrogen as a fuel is innovative, very complex and involves a wide range of technologies, disciplines of science and stakeholders.
- There are no predetermined answers; the problem has an interdisciplinary character and is therefore best answered by an expert panel representing different stakeholders in the marketing process.
- It is necessary to obtain information about future scenarios as perceived by experts, taking into account the fast technology development as well as the rapid tightening of societal demands towards clean, sustainable and efficient mobility of persons and goods. Furthermore, events like the nuclear accident in Fukushima, the Arab revolt or the Ukrainian crisis have a dramatic and far-reaching influence on the driving factors of the market introduction of hydrogen as a fuel.
- The complex scientific and economic dimension of the problem needs far-reaching decisions. Today, there are no more ‘universal experts’ who would be able to take or guide a decision on their own, but a group of highly-specialised experts (expert panel) is perceived as being capable of describing a problem well and deriving the right conclusions. The decision-makers need a consensus from this larger group of experts as a guideline.
- The relevant time horizon of the decision is long and far-reaching decisions are normally affiliated with high costs and uncertainty, thus the decision process becomes more and more complex and elaborate. [Wolf et.al. no year, p. 1-10; Häder, 2002, p.3]
- Finally, the problem can be described (see previous chapters), thus the principal design of the Delphi-Analysis can be elaborated in a questionnaire.

6.3.1 Elements and organisation of the Delphi-Analysis

The Delphi-process uses an iterative, anonymous group communication process that, in principal, involves mailing repeated rounds of questionnaires, including a controlled feedback process, to a selected group of respondents, considered to be experts in a given subject matter area. The organisation of the Delphi-Analysis was carried out in stages.

Step 1: Description of the problem: The Delphi-Analysis shall deliver information on the main drivers, drawbacks and competing technologies influencing the market introduction process of hydrogen fuel, measures that could support the market introduction of hydrogen fuel as well as main a timeline of the market introduction process.

Step 2: Decision about the type of Delphi-Analysis suited to the problem: The 'Type 3: Delphi-Analysis for investigating and qualifying the opinion of an expert panel on an unknown question' is typically applied to problems as described in Step 1.

Step 3: Development of a questionnaire: The questionnaire is either developed from the responses of the expert panel or by the operator of the Delphi-Analysis. In the first case, the experts receive a list of open-ended questions designed to collect their opinions about key issues of the problem to be investigated within the first round. The responses are analysed and summarised in a questionnaire. In the second case, the operator prepares the questionnaire using his own expertise and/or literature information. It was decided to elaborate the questionnaire solely by the operator to reduce the time burden on the experts. The first questionnaire was structured into five blocks with the option to add suggestions as to what else should be considered in the next questioning round. Every question left space for comments. The five blocks were (see also Annex 8.7 for the complete questionnaire):

- **Importance of selected alternative technologies in different vehicle categories** (cars and light duty vehicles, public transport buses, heavy duty vehicles for national and international freight transport) by 2030: the experts were asked about their opinion using a scale with five options (1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Moderately important; 5 = Very Important),
- **Expected changes in the German vehicle market by 2030**: the experts were asked for an estimation of the changes in the registration of new cars (fuel, motorisation, segments) in Germany by 2020 and 2030 as well as some fuel specific questions,
- **Period within which defined events or developments which influence the market introduction of hydrogen fuel** would have occurred for the first time: the experts were asked for their opinion using a scale with six options (1 = between 2010 and 2014, 2 = between 2015 and 2019; 3 = between 2020 and 2024; 4 = between 2025 and 2029; 5 = 2030 and later; 6 = never),
- **Level of agreement to specific theses which influence the marketing process of hydrogen fuel** (time horizon until 2030): the experts were asked for their opinion using a scale with five options (1 = strongly disagree, 2 = disagree, 3= neutral, 4 = agree, 5 = strongly agree),
- **Importance, urgency and feasibility of defined short to long-term actions to further promote the market introduction of hydrogen fuel**: the experts were asked to evaluate different measures using three scales of five options (**Importance**: see above, **Urgency**: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later, **Feasibility**: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible). This question block was targeted at gaining information not only on the importance of a measure, but also at learning about when the specific measure should best be applied to have the greatest effect. It was also aimed at learning about how the experts evaluate the feasibility of a successful implementation of the respective measure.

The questions were elaborated using the author's professional experience, lessons learned from the investigations carried out within the framework of this thesis as well as discussions with various experts on the drivers and drawbacks for marketing hydrogen fuel.

The use of a standardised questionnaire allowed a panel of geographically dispersed experts to be consulted systematically and anonymously about a complex problem. The questions were designed to elicit and develop individual responses to the problem posed. The main point behind the Delphi-Analysis is to overcome the disadvantages of conventional methods such as pooling opinions obtained from direct group discussion or questioning of experts without any group interaction. The main disadvantages of the direct group discussion are the influence of a 'spokesman' who determines the group's opinion as well as costs and organisational effort. Within a thesis work it seemed unrealistic to attract a high-ranking group for participation in a direct discussion panel. The financial means to cover at least travel costs, accommodation and the conference room could easily go up to five figure Euros.

The questionnaire was sent to experts in the fields of H_2FC and other alternative fuel technologies, thus specific technical terms were used without further explanation. However, the estimation tasks were amended by the current values as far as available, e.g. question 8 on the future share of biofuels and question 19 on the future carbon costs. The questionnaires were sent via e-mail midweek to motivate completion during the weekend. The questionnaires could be sent back by email, fax or ordinary mail. The majority of questionnaires from the first questioning round were received by email; only two were sent by ordinary mail and one was handed over personally.

The questionnaire was designed to be filled in either manually or electronically to have a positive effect on the return rate. It was decided to limit the survey to a maximum of 50 questions, because also, the length of the questionnaire significantly influences the return rate. Discussions with some experts after the first questioning round showed that this was an acceptable effort for the experts.

Step 4: Pre-testing of the questionnaire: The questionnaire was pre-tested with the help of two experts, i.e. in a kind of small pre-round. The pre-test was targeted at achieving

- Proper wording, e.g. ambiguities, vagueness,
- Comprehensibility of the questions, in particular of the technical terms used,
- Resolvability of the questions,
- Interest and attention of the experts during working out of the questionnaire, in particular, length of the questionnaire and level of detail of the questions,
- Technical correctness of the questionnaire, in particular, whether all instructions for filling in the questions are well understood,
- Reasonability of time demand for filling in the questionnaire. [Häder, 2002, p. 138-139]

In general, two strategies exist for pre-testing the questionnaire. For the use of the think-aloud-technique, the tester is asked to commend loudly during responding to the questions. For the use of the probing technique, the pre-tester is questioned about his responding strategies, the comprehensibility of the questions and how he retrieved the relevant information. [Häder, 2002, p. 138-139]

Within this thesis the probing technique was used. The two pre-testers filled in the questionnaire and were interviewed about their experiences. As a result, some questions were reformulated. Furthermore, within the block of questions "Expected changes in the German vehicle market by 2030", the level of detail was reduced by merging some sub-groups. The comments on the questionnaire by the expert panel showed that this section was still the most difficult one to be answered.

Step 5: Decision on the number of Delphi-Analysis questioning rounds: it was decided to run two Delphi rounds, again to reduce the time burden on the experts. This was communicated already with the sending of the first questionnaire. Studies showed that the biggest change in opinion takes place between the first and the second round. Two rounds are quite common for the selected type of Delphi-Analysis, as the main aim of the analysis is the qualification of the expert panel's opinion and not to gain exact figures. [Häder, 2002, p. 119] After finalisation of the second questioning round the level of consensus reached during the Delphi process was accessed through an analysis of the stability of the expert panel's responses in the successive iterations:

In the ***First thematic block*** / ***Fourth thematic block/ Fifth thematic block*** no change of the median occurred for any question or sub-question between the two questioning rounds.

Second thematic block: '*Expected changes in the German vehicle market by 2030*': The results of this thematic block were evaluated using the statistical mean, but only a few changes in the percentages occur. In the following shifts larger than ±1% are summarised:

	Round 1	Round 2
8a) Future new petrol car registrations in % in Germany by 2030	39.0%	37.7%
8b) Future new diesel car registrations in % in Germany by 2030	38.9%	40.1%
9) Future hybridisation rate of newly registered cars in Germany by 2020	13.7%	15.0%
11a) Future new mini and small car registrations in % in Germany, 2030	36.3%	37.3%
11d) Future new other car (SUVs, utilities, vans etc.) reg., %, Germany, 2030	20.8%	19.6%
12a) Future new car registrations up to 50 kW, in %, Germany, 2030	11.9%	10.8%
13) In Germany H_2-transport fuel will be produced centrally... by 2030	75.2%	76.4%

Third thematic block: *Period within which [...]*: Only a few differences of the median occurred between the first and second round. The hybridisation of vehicles with spark ignition was postponed from 2014/2015 (median of 1.5) to the period of 2015-2019 (medium of 2). The operation of spark-ignition-engines on an H_2-methane blend was postponed from the period of 2015-2019 (median of 2) to 2019/2020 (median of 2.5).

Already after two iterations quite a high level of stability of the experts' answers was reached. Thus, the original announcement to keep within two rounds of questioning proved to be well chosen. This result coincides with literature that experts in a thematic field are not too ready to change their mind.

Step 6: Selection of Delphi-Analysis expert panel: the careful selection of participants is important since the quality and accuracy of the responses to a Delphi-Analysis are only as good as the expertise of the participants involved in the process. **Experts** are defined as people researching or working in the relevant field of interest. The participation of executive managers is preferred. The experts are seen as a group, because it is the group of experts, their knowledge and authority that solves the problem. The experts are anonymous to one another, thus group effects and individual interests do not influence the decision-making process. Furthermore, each individual expert is free to change his/her opinion during the course of the analysis without a loss of face.

The size of the expert group depends upon the purpose of the Delphi-Analysis and the diversity of the targeted population. Where the sample is homogenous, a smaller sample is possible than from a heterogeneous population. In any case, it was shown that, in general, the results improve with the size of the group. However, the management of the Delphi-Process and the analysis of the data become cumbersome in return for marginal benefits above a certain threshold. A minimum number of seven to twelve experts as well as a maximum of 25 to 30 experts is recommended in literature. [Häder, 2002, p. 94; Hartman et. al. 2007, p. 1-2, 10]

Literature does not provide certain criteria concerning the selection process for the expert panel. Therefore, it was decided to use a quite practical experts selection approach. The number of experts working in the H_2FC niche market is quite small. The operator of the Delphi-Analysis has twenty years professional background in the alternative fuels business. Based on this experience a list of 55 possible experts from various sectors and different geographic regions, including neighbouring European countries was drawn up. In addition, experts for propulsion systems competing with H_2FC-technology were invited to participate in the process. It was expected that these experts would contribute with more critical comments on the market introduction process of hydrogen as a fuel. This expectation proved to be true.

A representative number of experts from different sectors was selected, because literature warns that experts who are actively working on a topic tend to evaluate the progress in their working field much more positively than others. For the evaluation of the results, this procedure also allows the data to be assessed according to these sectors by generating different layers of samples. [Häder, 2002, p. 92; Hsu et. al., 2007, p.3] Experts were selected from the following sectors:

- **Vehicle manufacturer**: experts engaged in R&D, e.g. H_2FC vehicle technology. It was possible to gain six experts, representing four large international vehicle manufacturers (two from heavy duty vehicle and four from car manufacturing).
- **University/R&D institutes**: experts researching on H_2FC-technology issues. Five experts participated in the first round; one expert had to cancel his participation in the second round due to a heavy workload.
- **Public administration**: including experts from associations which are founded and funded by the government to administrate, run or promote the various support projects on different Federal levels. Seven participants from this sector participated in the first round, six in the second round.
- **H_2FC-system developer**: experts from the manufacturers of H_2-infrastructure or FC-technology. The European expertise in this sector is small compared to the US; nevertheless, it was possible to gain three experts participating in both questioning rounds.
- **Fleet operator/User**: this group comprises users at different levels of a company; e.g. fleet operators as well as direct users of FCVs. Currently, there are not many fleet operators or users available who have had the chance to gain experience with H_2FC-technology. In any case, it was possible to gain five experts with experience in the operation of H_2-propelled cars, buses and other applications for both questioning rounds.
- **Mineral oil / Energy company**: Experts from the wider energy sector, such as from the mineral oil industry who are active in the construction of an H_2-infrastructure and in the development of clean green energy to produce hydrogen. Three experts representing the electricity, mineral oil and industrial gas industry participated in both questioning rounds.
- **Consultancy**: Seven experts from consultancy companies accompanying the market introduction process of hydrogen fuel, working in the fields of alternative energy or active for the lobbying of natural gas as vehicle fuel participated in both questioning rounds.

All experts are very competent in their working field and hold leading positions. They cover a balanced experience from those sectors which have an important role to play during the market introduction process of H_2-fuel (see *Figure 6-22*). All experts were contacted before the start of the Delphi-Analysis to confirm their readiness to participate.

Step 7: Acquisition of experts, sending process and return rate of completed questionnaires: it was possible to contact 47 of the 55 experts listed either by telephone or email in the run-up phase to the Delphi-Analysis in summer 2010. 43 of these experts agreed to participate in the Delphi-Analysis. These experts received the questionnaire of the first round together with an accompanying letter. The questionnaire was sent immediately after agreement was received for the expert to participate. Both questionnaire and accompanying letter (Annexes 8.5 and 8.7) were elaborated in English and German to keep the barrier to filling in the questionnaire low. The cover letter for the first questioning round included an explanation of the aim of the analysis, a short description of the methodology and the procedure of the Delphi-Analysis as well as an annotation on data privacy. It also promised a "reward" for answering the questionnaire: a summary of the feedback from the other experts and a copy of the full report on the Delphi-Analysis was presented to each participant. Furthermore, technical aspects were explained such as how to fill in the questionnaire, where to send the response and how to contact the "help desk". Gratitude for co-operation was expressed. The questionnaire also asked for permission to publish the expert's name, company and position on a list to be sent to all participants and to be published within this thesis. The list should help the experts to recapitulate their answers, because it has been shown that the readiness for a change of an opinion is larger when the credibility of the expert panel is ensured, (Annex 8.4). [Häder, 2002, p. 94]

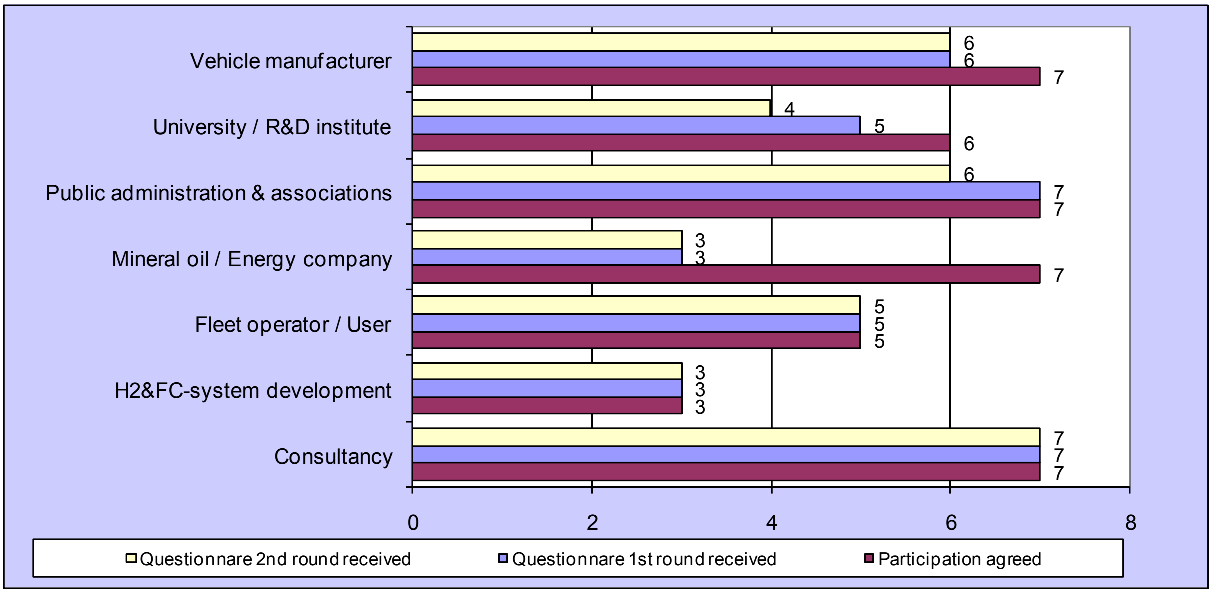


Figure 6-22 Participation quota in the Delphi-Analysis

Finally, 42 experts agreed to participate and 36 experts (86%) answered the first questionnaire. This high response rate was reached after a prolongation of deadline and personal reminders to belated participants. In October 2010, all 36 participants from the first questioning round were contacted for the second round. Together with the adjusted second questionnaire they received a summary of the group's answers and comments from the first round (Annexes 8.7). In addition, after completion of the second questioning round, a summary of the raw data (Annex 8.8) was sent to all participants together with another acknowledgment for participation. Experts with due contributions were reminded by mail and in person. By doing so it was possible to encourage 34 experts to participate in the second questioning round until the end of 2010; this equals a 94.4% response rate or an 81%

response rate considering the original group of participants. This extremely high response rate is ascribed to the personal approach of the participating experts and the high attention the topic of the questionnaire is receiving in current public discussion. About 20% of the experts questioned work primarily on H_2FC-technologies, the majority is involved more broadly in “green” transport issues.

Step 8: Feedback and iteration process: Information is processed by an individual in a permanent cyclic feedback between perception, memory (available knowledge base) and search for more information. As a consequence, the knowledge of the individual may be updated. This cycle improves the quality of the answer, shall stimulate a learning process and may lead to a greater consensus between the experts. This process was used during the iteration process of the Delphi-Analysis. [Häder, 2002, p. 41-51] In the Delphi-Analysis, the experts' assessments are made under sub-optimal conditions, because the problem is complex, the future is unknown and lots of alternative scenarios are possible for one answer. In addition, the various issues requested in the questionnaire often influence one another and the resulting consequences take different dimensions. [Hsu, et. al., 2007, p. 2]

In each of the two Delphi-rounds, every expert worked through a questionnaire providing comments, questions or answers. The experts each received a **summary of the comments** given by all experts. Thus, each expert indirectly participated in the discussion process which relates to the process. The comments received varied from spontaneous remarks to detailed information on the topic. In addition, comprehension and interpretation problems for some of the questions could be identified. In these cases, more information was handed in with the second questionnaire. In addition, the **individual responses to each round were summarised, visualised using statistical means** and communicated. Besides the anonymity of the experts to one another, the use of statistical tools further reduced group pressure for conformity, because the statistical analysis ensured that the opinion of each individual taking part in the Delphi-Analysis was well represented in the feedback process. This **feedback process** enabled the experts to refine their views as the group's work progressed. The whole process seeked agreement, disagreement and insights.

Step 9: Adaption of the questionnaire for the second round: The group's values for median or mean were added to each question and compared with the individual answer of the respective expert. Thus, in the second round personalised questionnaires were sent out (see *Figure 6-23* for an example). In addition, some experts were reminded to complete the **annotation on data privacy**. Some experts pointed out **mistakes or impreciseness** in the first questionnaire, these were corrected (all changes in the wording of the questions were marked in the questionnaire in *italic*.): In Question 15, it should say “Use of ethanol E85 (mixture of 85% ethanol and 15% petrol)” instead of “Pure use of ethanol”. In addition, the “Use of second generation biofuels” should include only “BTL: Biomass-to-Liquid”.

Some experts asked for further definitions of some aspects, i.e. in Question 6: ‘*biofuels of the second generation’* were defined as fuels produced from all parts of a plant or waste materials. In Question 9 ‘*hybridisation*’ was defined as all additional energy storage with a minimum capacity of 5 kW_{el}. In Question 18 and 19 the term ‘*vehicle*’ was restricted to at least 4 wheelers without wheelchairs etc. As many experts voted for more than one answer in these questions, a reminder was put to *give only one answer*. Government measures which could increase *CO_2-emission costs* were explicitly included in Question 27. In Question 28 the term ‘*sustainable*’ was defined in accordance with the Brundlandt-Report "to make development sustainable [is] to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs".[257] In Question 31 '*Sustainable products and services*' shall comply in terms of efficiency and environmental friendliness to the state of the art, i.e. use up-to-date processes, equipment and operation methods. In Question 35 the term '*large infrastructure projects*' was elucidated by some examples.

Delphi - Questionnaire on the market introduction of hydrogen fuel

Your individual responses to the Delphi expert consultation will be handled confidentially and anonymously.

!Please mark only one answer per question!

Use of various alternative technologies for different vehicle classes in Europe (*in particular Germany*) by 2030

1 The use of fuel cell technology will be important for the application in ...
(please mark the importance)

	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
a) cars and light duty vehicles						5	5	
b) buses of the public transport						5	5	
c) trucks of the national and international freight transport						2	5	

Changes in the German vehicle market by 2030

8 Future new registrations of cars according to fuels in % in Germany
- hybrids and biofuels are subordinated to the respective fuel concept, see also question 9 & 10
- about 40,000 cars equals 1%
(please estimate future fuel shares)

	2008	2020	2030	Group's mean 2020	Group's mean 2030	own judgement 2020	own judgement 2030	Comments
a) gasoline	54,9%			46%	39%	40%	20%	
b) diesel	44,1%			45%	39%	35%	15%	
c) LPG	0,5%			2%	3%	1%	2%	
d) CNG	0,4%			2%	3%	1%	2%	
e) electric battery vehicle	0,0%			3%	7%	13%	35%	
f) hydrogen	0,0%			2%	9%	10%	25%	
g) others	0,2%			1%	1%	1%	1%	
Sum (control)	100,0%							

Figure 6-23: Example of a personalised questionnaire from the second round of questioning

The questionnaire left space for suggestions from the experts and ended with the invitation to formulate new ideas. The results of the open question were included in the second questionnaire, e.g. Question 14 on H_2-transport fuel production procedures was extended by electrolysis using electricity from coal power plants in combination with CCS, and thermochemical processes (above 1,700 °C water vapour dissociates to H_2 and O_2). New measures to promote the market introduction of hydrogen as a fuel were added in Questions 51 to 53:

- Payment of an "H_2-Cent" - charged from each litre of petrol or diesel sold - to the building-up of a hydrogen infrastructure,
- Financial support for the production of regenerative hydrogen,
- Procurement plan to equip the fleets of ministries, public organisations etc. with FCVs.

Originally, it was considered to eliminate questions from the first round which the experts would have difficulties answering or questions that they would evaluate strangely. This was not the case, thus no question was deleted for the next questioning round.

257 http://www.un-documents.net/ocf-ov.htm#I.3, 22.12.2010

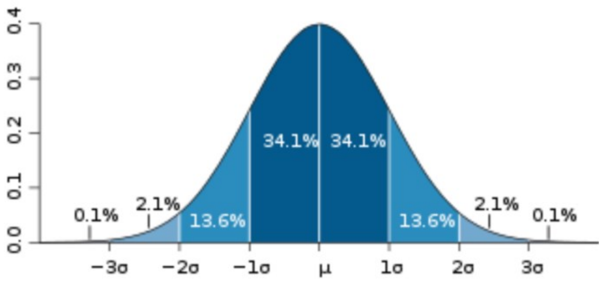
Step 10: Detailed analysis of the results of the questioning: In the follow-up to the questioning process a detailed evaluation of the Delphi-Process and the results of the Delphi-Questionnaires was carried out, see below. The statistical tools used in this Delphi-Analysis are measures of central tendency (mean, median, mode) and level of dispersion (standard deviation, inter-quartile-range):

- The **mean** μ describes the sum of observed values divided by the number of observations *n*. It could not be used if the question includes open ended intervals or if the intervals are not equally sized.

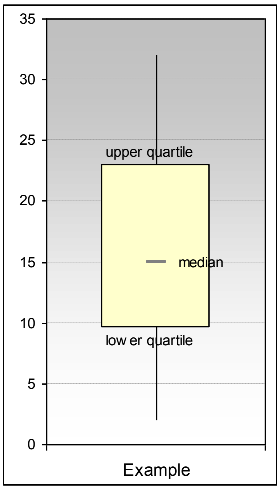
$$\mu = \frac{\sum_{i=1}^{i=n} x_i}{n}$$

- The **standard deviation**[258] **σ** is calculated from the square root of the variance of the single values from the mean. It is a measure for uncertainty. For example, in a 'normal distribution', 68.2% of the values deviate plus/minus one standard deviation from the mean, 95% of the values are within a range of plus/minus two times the standard deviation from the mean.

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2}$$



- The **median** is the numeric value separating the higher half of a sample from the lower half, i.e. it is the middle value of a set of sorted data containing an odd number of values or the average of the two middle values of a set of data with an even number of values. The median could be used if open time horizons are requested by the expert panel.
- **Boxplots** are a tool of descriptive statistics and display differences between populations. They summarise five numbers: the sample minimum, lower quartile, median, upper quartile and sample maximum. It consists of a box and two lines, extending the box. The end of the lower line marks the sample's minimum, the end of the upper line its maximum. 50% of all values are located within the box (**inter-quartile range**), i.e. between the 25%-quartile and the 75%-quartile (25%/75% of all values of the sample are smaller than these values). The median divides the whole diagram into two parts, on both sides are 50% of all values, visualising the dispersion (spread) and skewness in the data.



6.3.2 Results of the Delphi-analysis

6.3.2.1 Importance of the different alternative technologies in different vehicle categories

The Delphi-Analysis asked the expert panel about the importance of four different alternative technologies in three vehicle categories (cars & light duty vehicles (LDVs), public transport buses and national and international freight transport trucks). The summary of the raw data including all comments by the experts in the second round are depicted in Annex 8.8. The technologies are:

- Use of H_2FC- and H_2ICE-technology: combined with the question on the most important storage technology (GH_2 at 35/70 MPa or LH_2),
- Use of biofuels of the second generation,
- Use of battery electric vehicles.

[258] Graphic from: http://en.wikipedia.org/wiki/Standard_deviation

The results of the inquiry are summarised in *Figure 6-24*. The results are evaluated in the following for the different vehicle technologies. *Figure 6-25* depicts the absolute numbers of answers that were changed. A positive number shows that the overall sum of answers was corrected to a higher importance level, a negative number indicates that the balanced answers devaluated the importance of the respective technology. If the valuation of the respective technology decreased the number was marked in red.

	FC-technology	H_2ICE-technology	35 MPa CGH_2 storage	70 MPa CGH_2 storage	LH_2 storage technology	Biofuels of the second generation	Pure battery-electric propulsion
will be important for the application in ...							
LDVs	Very important	Low importance	Neutral	Very important	Low importance	Important	Important
Buses	Very important	Low importance	Important	Important	Low importance	Important	Low importance
Trucks	Low importance	Low importance	Low importance	Low importance	Low importance	Important	Not at all important

Figure 6-24: Evaluation of the expert panel on the use of various alternative technologies for different vehicle classes in Europe (in particular Germany) by 2030

	FC-technology	H_2ICE-technology	35 MPa CGH_2 storage tech.	70 MPa CGH_2 storage tech.	LH_2 storage technology	Biofuels of the second generation	Pure battery-electric propulsion
LDVs	+4/-1 +3	+1/-4 -3	+4/-5 -1	+6/-1 +5	+2/-7 -5	+6/-3 +3	+1/-3 -2
Buses	0/0 0	+4/-5 -1	+5/-3 +2	+6/-4 +2	+1/-8 -7	+2/-3 -1	+2/-10 -8
Trucks	+3/-2 +1	+3/-7 -4	+1/-7 -6	+6/-8 -2	+4/-7 -3	+2/-6 -4	0/-9 -9

Figure 6-25: Evaluation of the readiness of experts to change answers on the use of various alternative technologies for different vehicle classes in Europe by 2030[259]

The attitude 'readiness to change the own answer' in the second questioning round was analysed for all qualitative questions. "Readiness to change" was defined as:

$$\text{Readiness to Change} = \frac{\text{Number of answers changed during Delphi process}}{\text{Total number of answers}}.$$

The evaluation of opinion changes from the individual expert during the Delphi process gives a clue as to how deeply convictions on single aspects are rooted. In addition, it may also depict current developments, e.g. pullback of a large manufacturer from one technology or affirmation of a technology in a pilot project during the time frame of the Delphi process. The highest Readiness to Change was observed in a question about the effectiveness of an H_2-fuel promotion measure with 50%. Therefore it was decided to use a scale of five categories with a step size of ten percent each to visualise the readiness to change. In all cases, the experts changed their answer only by one category up or down:

259 Number of experts changing mind (positive figure: pro importance of technology; negative figure: contra importance of technology)

Readiness to change	Very high >40-50%	High >30-40%	Neutral >20-30%	Low >10-20%	Very low 0-10%

CARS AND LIGHT DUTY VEHICLES (LDVS)

The expert panel was asked to assess the importance of different alternative vehicle technologies in Germany by 2030. The experts clearly evaluated FC-technology best for the application in LDVs (mean of 4.5) using 70 MPa technology (4.4), followed by BEVs (3.8) and biofuels of the second generation (3.6). Thus, three out of four technologies offered were judged to be at least important and suitable for use in LDVs.

FC-technology was considered as very important (61%) or at least important (30%) for use in LDVs by 2030, only 3% did not see a future for FCVs. In particular the combination with 70 MPa technology, which increases the vehicle range close to the range of conventional vehicles was judged favourably (see *Figure 6-26*). FC-technology was assessed to be increasingly important during the Delphi process, even if the technology was not in the media that often. However, several important activities determined the interest of the industry in the technology. This included the 'Memorandum of Understanding' of the 'H_2-mobility initiative' to evaluate the set-up of an H_2-infrastructure in Germany (09/2009), Toyota presented its $FCHV_{adv}$ (02/2010), the Federal State of North Rhine-Westphalia became a CEP member (05/2010) and Honda offered its FCX Clarity for lease to everybody in California (07/2010).

The experts highlighted "*the advantages of FCVs, such as the high efficiency, the use of a fuel with a wide primary energy basis, local zero-emissions or the potential of FC-technology as a range extender for BEVs. Experts criticised the need for an H_2-fuelling infrastructure. One expert, judging FCVs neutrally in the second round, remarked that "the size of the FC system & added expense will continue to be a long term impediment". [Jeff Seisler, chairman of ENGVA]*[260]

Combustion of hydrogen in an ICE: the H_2ICE was seen by none of the experts as a very important future technology option for passenger cars, LDVs or trucks. Only 12% considered H_2ICE as being important at all. During the Delphi-process the acceptance of the technology decreased. Today, no vehicle manufacturer is following this technology pathway any longer, see section 4.2.4.5 for a list of manufacturers which constructed (pilot) H_2ICEs-vehicles.

Experts complained about low efficiency and high costs: *"I know of no OEM who is looking at this technology and it is at best an interim solution due to the existence of some emissions. High fuel consumption, high fuel costs and the low mileage would work against H_2ICE-technology. Efficient diesel hybrid vehicles would be more competitive. For all sectors efficiency is lower & W2W results are not as good as dedicated FCs. The energy efficiency is low. A high fuel consumption reduction could be reached by hybridisation and use of small volume H_2ICEs in cars and buses."*

Hydrogen on-board reforming: The Delphi-Analysis abandoned the option of on-board H_2-reforming from liquid carbon fuels such as petrol or methanol. Reforming was only favoured during the development of early FC prototypes, see section 4.2.4.2.

Hydrogen storage: The expert group shared a quite homogeneous opinion about the way of H_2-storage in LDVs. 88% of the experts considered 70 MPa CGH_2-storage as a very important (or at least of some importance) technology for the application in this vehicle category. The 35 MPa CGH_2-storage technology was evaluated as a very important or at least an important future technology by only 32% of the experts. Naturally, the fleet operators and users within the expert group evaluated 35-MPa-technology as the worst due to the large range disadvantage, see section 4.2.4.4. They voted between "not important at all" and "neutral". The representatives of the mineral oil industry opted best for the 35-MPa-

[260] Experts' comments are highlighted in italic letters.

technology (“neutral” to “important”). The application of 70-MPa-technology is difficult, this could explain the hesitation of the mineral oil industry.

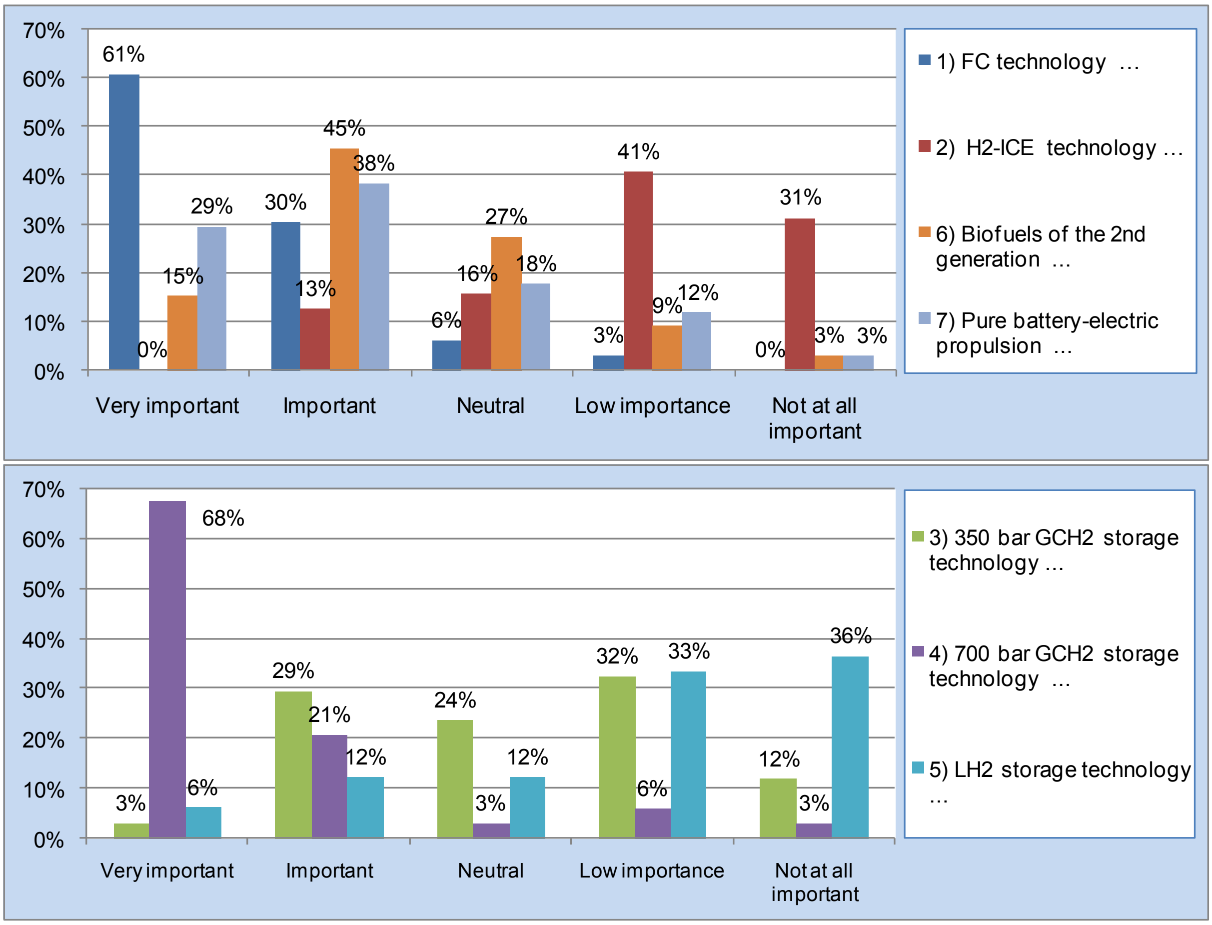


Figure 6-26: The use of …. will be ... for the application in LDVs in Europe (in particular Germany) by 2030

During the Delphi-process support for **GCH_2-70-MPa-technology** increased strongly, in particular for LDVs, whereas backing for 35-MPa-technology and LH_2-storage decreased. The experts opted for the 70-MPa-CGH_2-technology although this technology was not mature in 2010. Also standards, e.g. SAE J2799 defining “70-MPa-CH_2-surface-vehicle-fuelling-connection-device and optional vehicle to station communications”, were still provisional and in the testing phase. The experts remarked that

“*... 35-MPa-technology may be an intermediate stage towards 70 MPa, but the final pressure could also be in-between, e.g. 50 MPa for CGH_2. 35-MPa-technology may play a larger role for LDVs in local fleets, e.g. urban delivery vans with only small daily mileage and access to a determined filling station. Anyhow, the increase in pressure reduces the space constrains within the vehicle. Range was addressed as a main issue in particular for 35-MPa-filling technology. One expert remarked that slow-fill 35-MPa-technology is acceptable to buses due to the different refuelling regime*.”

Liquid hydrogen was rejected by the expert panel as a storage option. Only 18% of the experts rated this storage option ‘important’ or ‘very important’, but 70% evaluated it as ‘not important’ or ‘less important’. In particular, representatives from the mineral oil industry judged the sustainability of this technology critically. Expert opinion is confirmed as applications in FCVs are no longer available.

Biofuels of the second generation were judged by 61% of the experts as ‘very important’ or ‘at least important for the future transport sector’. Only 12% evaluated them as ‘less important’ or ‘not important’. Noticeably, 27% demonstrated a neutral position towards biofuels. One of the reasons may be that there is currently not much information on the technological progress of second-generation biofuels, they have not yet been produced commercially. The evaluation of biofuels improved slightly during the Delphi-process.

"*Biofuels are suitable to cover all mobility needs. Will extend the range of renewable fuels but not environmentally sustainable in the long run. Limited potential, only for a transformation period. Due to the low percentage in the fuel mix, only of less importance. Blending to conventional fuels. Designer fuel for a clean combustion. Focus on heavy duty and airborne applications which need a high energy density. There will be not enough.*"

Future use of Battery Electric Vehicles: 67% of the experts considered BEVs as 'very important' or 'at least important for the use in LDVs by 2030', but 15% also assigned only a minor role to BEVs. BEVs were devaluated during the Delphi process. This happened despite several important activities taking place during the timeframe of the Delphi-process:

- Foundation of the National Platform Electro-mobility in May 2010,
- Introduction of the Mitsubishi I-MiEV, Nissan Leaf and other BEVs in Europe in 2010,
- Start of eSmart (Daimler, RWE) and eMini (BMW, Eon) demonstration projects, strong presentation of BEVs at the IAA in Hanover and the Paris Autosalon in 2010,
- Publication of the widely noticed first NEP interim report in November 2011.

In any case, BEVs have been riding on a media wave over the past couple of years. The appearance of the first pilot vehicles with all restrictions and publication of vehicle prices may have reduced this euphoria. These doubts also run through the comments of the experts as a common theme:

"Limited to urban use, only small vehicle with low daily mileage, depending on level of electrification (hybridisation). But the BEVs also have the same inherit advantages as FCVs: they are locally zero-emission vehicles and the electricity could be produced from manifold primary energy sources."

Furthermore, by the end of 2010 it became public knowledge that Mercedes stopped the development of the electric A- and B-class, postponing the planned market introduction in 2012 to the "future" and focusing instead on the market introduction of an REV in 2014 and the F-cell in 2015.[261] Additionally, the conditions for the construction of charging points in public areas and access to this public infrastructure are unclear, e.g. billing, discriminatory access to charging points of all suppliers, "roaming" etc.

PUBLIC TRANSPORT BUSES

There are several FC-bus demonstration projects in Europe and in the US. The expert panel gave a quite clear assessment on FC technology application in buses, (see *Figure 6-27*). Again, 91% evaluated FC-buses as 'important' or 'very important'; only 3% pointed out that this technology would have a low future importance. The experts evaluated **H_2ICE-technology** negatively: no expert referred to H_2ICE as a very important technology for buses, but 21% saw it as important and 12% assessed it neutrally. Most experts evaluated H_2ICE-technology as being less (43%) or not important (24%) for buses. This technology was only applied by the Berlin bus company, but no further development of this technology is expected due to a lack of manufacturers' willingness or ability to invest in R&D.

67% of the experts assessed both 35- and 70-MPa-**H_2storage technology** as very or at least important for bus operation. Currently all FC-buses in operation use 35 MPa technology, which is cheaper and more mature. LH_2-storage technology was evaluated as not or less important by 64% of the experts.

261 http://www.focus.de/auto/news/mercedes-a-klasse-e-cell-nicht-mehr-nur-mit-strom_aid_589699.html; 06.01.2012

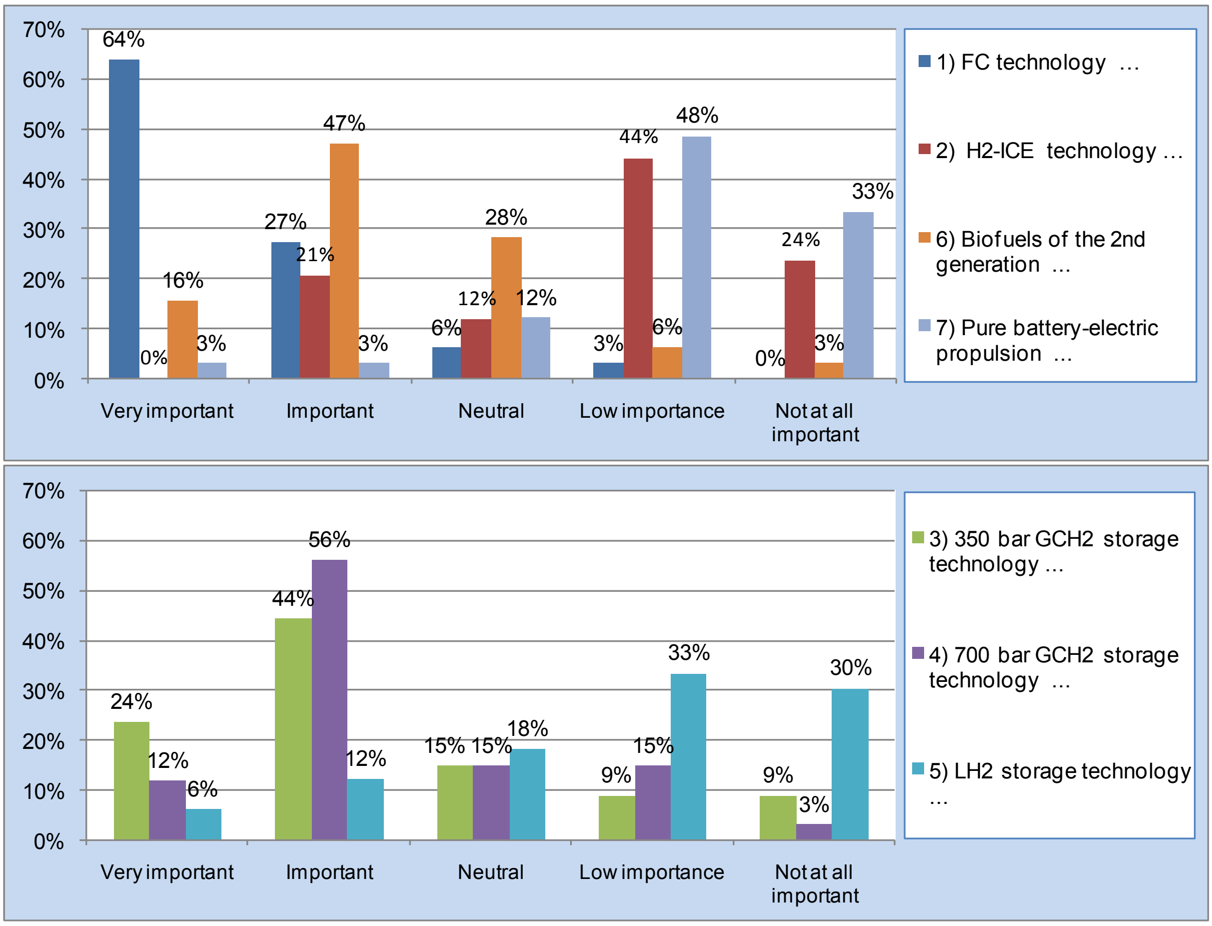


Figure 6-27: Use of various alternative technologies for buses in Europe (in particular Germany) by 2030

BEV-technology fared even worse: 82% of experts evaluated electric propulsion for buses as being of low importance or not important at all.

FC-buses would support the H_2-fuel supply in general and contribute towards achieving larger number of FC-stack sales. However, as shown with CNG buses, these vehicles are mainly fuelled at depots with no public access. FC-cars will not directly benefit from the bus H_2-filling infrastructure because mainly 35-MPa-technology is used and the hydrogen flow (100 gH_2/s) is not suitable for FC-cars (8 gH_2/s). The market perspective for FC-buses is evaluated differently. The EU CHIC project is targeted at moving H_2-FC powered buses towards full market commercialisation starting in 2015. However, the bus market is very much characterised by national requirements and manufacturers.

NATIONAL AND INTERNATIONAL FREIGHT TRANSPORT TRUCKS

The expert panel assessed the future propulsion for national and international freight transport trucks quite clearly. Only 6% saw FCs as an important option, 21% were neutral and 73% evaluated FCs as an option with low or no importance for trucks. H_2ICE was seen as even less an option: 12% of experts gave a neutral statement whereas 88% evaluated this as a technology path with low or no importance. If FC-technology is employed at all, the experts would prefer 70-MPa-technology (36% of experts voted at least neutrally), in contrast, 35-MPa-technology achieved only 21% at least neutral votes and LH_2-technology 27%. The experts remarked as follows:

"*Due to the reduced storage density of hydrogen, the range of the trucks would be too much limited, in particular as the competing diesel technology shows a high efficiency and fuel storage density (i.e. range) when highway driving. Application weight and range sensitive. The use of a FC as APU has* *some potentials, but a suitable fuel for the FC needs to be provided (or diesel reforming). The development of suitable storage technologies is not in view. Depending on the density of the filling station network, but corridor-style fuelling will take time to develop. H_2ICE lacks the necessary efficiency to provide range for long distance applications of hydrogen fuel, if than applied in FC using 70-MPa-storage technology. While these may be the last vehicles to adopt FCs, it is hard to see what else will replace diesel*."

Only a few demonstration projects exist for FC-trucks, e.g. the Delphi APU or a truck with a gross vehicle weight rating more than 15 t powered by an H_2FC within the Clean Truck Program at the Port of Los Angeles Vision Motor Corp.[262]

Opinion on BEV-technology for trucks is even more harsh with 100% of the experts evaluating this technology as not being suited to this type of vehicle. Experts remarked as follows:

"*Required range cannot be provided due to low storage density. Hybrid HDVs will play a role, but no plug-in applications. Electric applications as auxiliary.*"

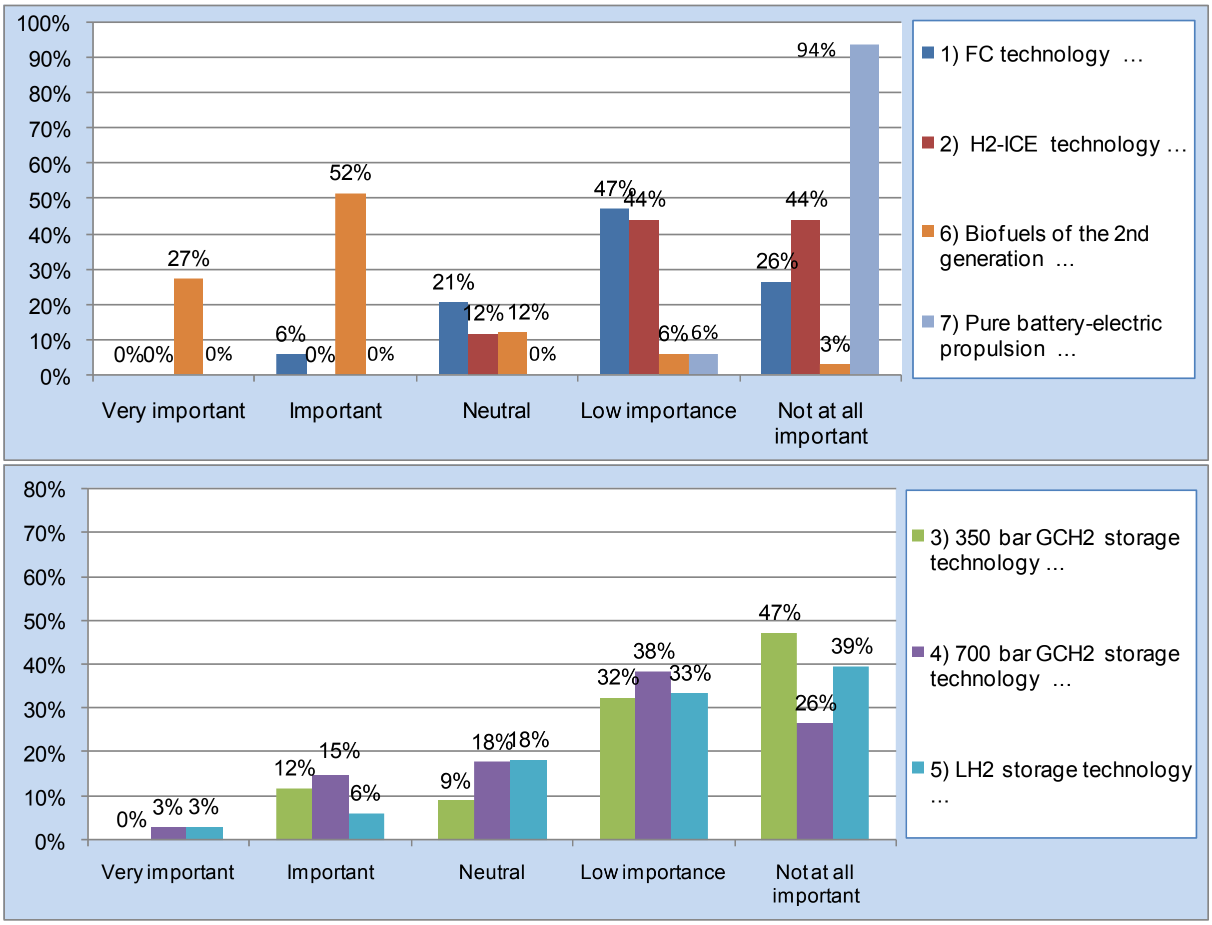


Figure 6-28: Alternative truck technologies in Europe (in particular Germany) by 2030

However, experts saw a good chance for biofuelled HDVs. 79% (91% adding the neutral position) stated that the use of biofuels will be very important or at least important for HDVs. Experts stated that biofuel application will focus on HDV and air transport which need a high energy density; for these transport means biofuels would be the only CO_2-mitigation option.

In summary (see *Figure 6-30*), LDVs and buses were evaluated as very suitable for FC-application by the expert panel. FC-buses achieved a mean of 4.5 using 35- or 70-MPa-H_2FC-technology (both 3.6). Battery electric propulsion was evaluated as important only for

262 https://www.portoflosangeles.org/environment/etruck.asp, 08.11.2015

LDVs (3.8). Biofuels were evaluated as suitable for all vehicles. It was the only option which was evaluated as important for use in trucks (3.9).

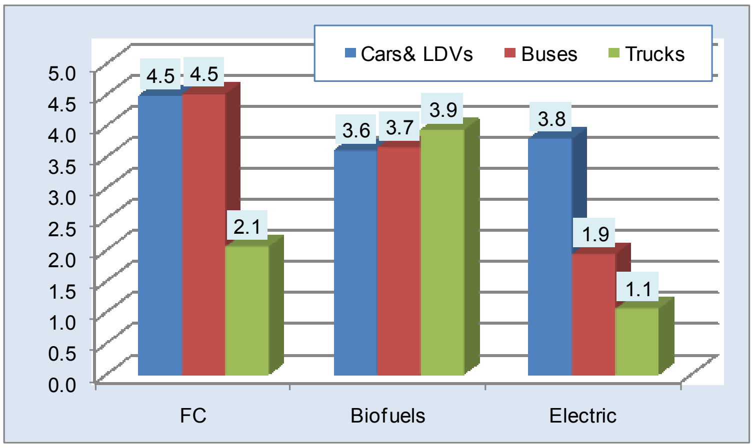


Figure 6-30: Importance of alternative drive systems

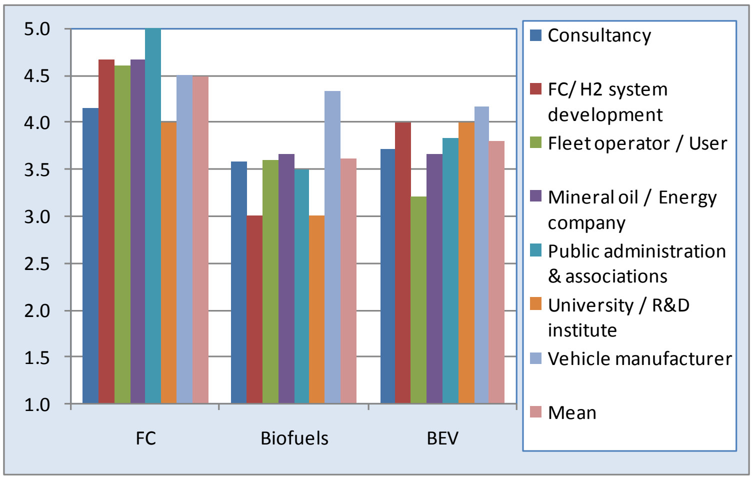


Figure 6-29: Sectoral vote on importance of LDV propulsion systems

The sectoral evaluation is quite interesting. *Consultants* voted FCV-technology significantly worse than the whole group, biofuels and BEVs were on the mean. The consultants involved were mainly from the industry. The reasons are speculative, e.g. frustration at slow progress. H_2FC system experts voted FCV- and BEV-technology above mean; they are involved in technology development and seem to have faith in their products. The *mineral oil and energy companies*, main investors in public infrastructure, evaluated the importance of FC-technology and biofuels slightly better than the whole group. BEVs were evaluated slightly less than the group's mean. *Fleet operators and users*, the most important group concerning the market success, evaluated FCV-technology and biofuels in accordance with the group's means. Their vote on BEVs differed significantly from the group's vote, being 0.6 points below the mean. This is the largest measured deviation from the mean in the Delphi-analysis. The *experts from public administrations and associations* gave high confidence in FC-technology (+0.5); biofuels and BEVs were evaluated close to the mean. The research sector voted comparatively negatively for FC-technology (-0.5) and biofuels (-0.6), BEVs received more confidence (+0.2). As researchers follow very specified and individual research targets, no interpretation of the results is possible. Experts from the *vehicle manufacturers*, the second large industrial investor in technology, assessed both biofuels (+0.7) and BEVs (+0.4) as particularly important. FC-technology was evaluated in accordance with the group's vote. However, for the sectoral analysis of the results, the size of the sample was very small, thus these results also reflect the individual opinions of the experts.

6.3.2.2 Expected changes in the German vehicle market by 2030

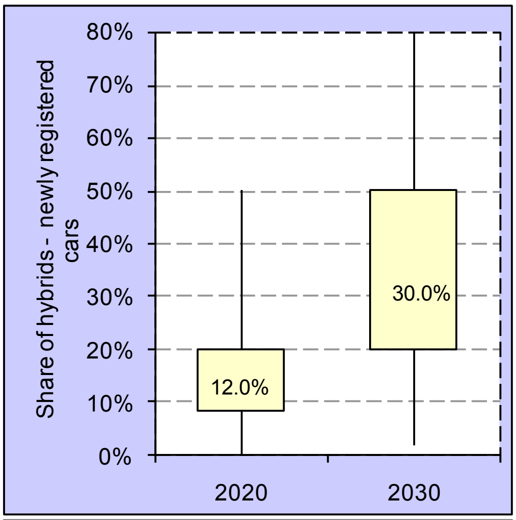
In the following, the expert panel's trends for the German vehicle market are depicted. Data refers to newly registered vehicles. The results of fuel share, hybridisation and biofuel rate are compared with literature data in *Figure 2-17*. A direct German/European comparison does not work in the short-term up to 2020, because Germany is a key market for several alternative fuels (at least CNG, biogas and hydrogen), today.

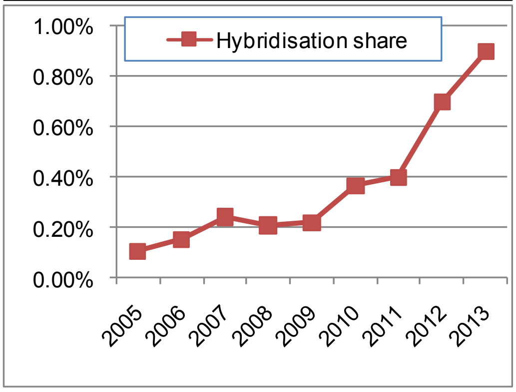
Question 8: Development of fuel shares (mean)[263]: The Delphi panel predicted a fossil fuel share of 95.6% by 2020 and 80.3% by 2030 (including CNG, which may be derived increasingly from biogas). Experts commented on the future fuel share as follows:

	2008	2020	2030
Petrol	55%	46%	38%
Diesel	44%	46%	40%
LPG	0.5%	1.7%	2.5%
CNG	0.4%	1.9%	3.3%
BEV	0.0%	3.1%	7.2%
H2	0.0%	1.8%	8.0%
others	0.0%	0.5%	1.1%

"LPG and CNG: Ongoing tax exemption is assumed, otherwise these options will diminish. BEVs only for urban mobility. H_2-infrastructure and sustainable production remains unclear."

Question 9: Development of hybrid share (mean), ("Future hybridisation rate of newly registered cars in Germany (additional energy storage with a minimum capacity of 5 kW_{el}, independent from the fuel used"): The experts estimated that the share of hybrids will increase from 0.2% in 2008 to **15%** (median 12%) by 2020 and **38%** (median 30%) by 2030, regardless of the second fuel used. The answers for 2020 range between 0 and 50%; the standard deviation is 11%. *50% of the answers are located between 8.5% and 20%.* The 2030 data range widely between 2 and 80%; the standard deviation is 25%. *50% of the answers are located between 20 and 50%*. During the evaluation process, both percentages of the hybridisation share increased by 1% for 2020/2030. Comments from the experts include: *"Including FCVs which are 100% hybridised. Same problem as with BEVs: limited resources to build the storage devices. Again, I believe a range of factors will lead to a complete hybridisation."*





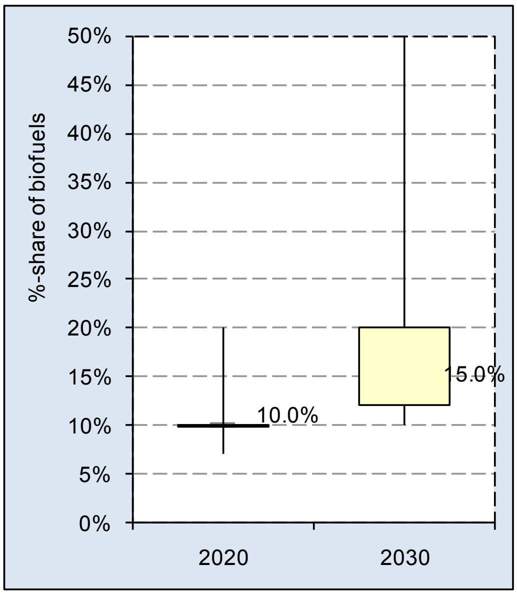
Maturing of hybridisation technologies for spark ignition and compression engines is expected by the expert panel between 2015 and 2019 (see below), making hybridisation a strong competitor for FCVs. During recent years the share of newly registered HEVs has grown. However, the model diversity available on the market is increasing only slowly. In 2013, k46.5 HEVs were registered in Germany, compared to M0.6 in the US where (P)HEVs reached a market share of 3.8%. Toyota was selling more than 60% of these vehicles, but Ford caught up with a large number of new models. [http://www.hybridcars.com/december-2013-dashboard/; 05.02.2014]

Question 10: Development of biofuel share (mean)[264]: The experts estimated that the share of biofuels will increase from 5.3% in 2009 to **10.6%** (median 10%) by 2020 and **17.1%** (median 15%) in 2030. The 2020 data range between 7 and 20%; the standard deviation is 2.7%. 50% of the answers are located at 10%. The 2030 data range between 10 and 50%; the standard deviation is 7.9%. 50% of the answers are located between 10 and 50%. Thus, the answers on the share of biofuels lie closer together than for the share of hybridisation.

263 Data for 2008-2013: kba, fz13

264 Data for 2009: own calculation using statistics of theFederal Office of Economics and Export Control: http://www.bafa.de/bafa/de/energie/mineraloel_rohoel/amtliche_mineraloeldaten/index.html

The means for 2020/2030 did not change during the evaluation process. Comments of the experts reflect:



"The total fuel market is shrinking due to increased efficiency, thus biofuels share increases. Only if EU mandates remain firm".

Question 15: Future role of biofuels in Germany (by 2030): in addition, the experts were asked to assess the future role of biofuels in Germany.[265] Four out of six biofuels options were evaluated as being important: The blending of biodiesel to diesel was assessed the highest (mean: 4) followed by the use of second generation biofuels (3.9), blending of ethanol to petrol (3.8) and blending of biogas to natural gas (3.7). The use of pure biodiesel (2.1) or E85 (2.3) was evaluated as not important. The high ranking of second generation biofuels is quite surprising as, to date, no commercial plant exists. Comments from the experts included: *"Pure biodiesel is already today „more or less done" due to the emission discussion (compatibility with particle filter). Maturing of second generation biofuels technology is delayed."*

The readiness to change the answers was quite low. Pure biodiesel was evaluated worse in the second round; the Delphi-process was carried out during the period of closing of biodiesel production facilities and filling points as a consequence of the reduced tax exemption of pure biodiesel. Biogas entered public discussion and evaluation increased.

a) Pure use of biodiesel	b) Use of ethanol E85	c) Blending of biodiesel to diesel	d) Blending of ethanol to petrol	e) Blending of biogas to natu-ral gas	f) Use of 2nd generation biofuels (BTL)
Future role of biofuels in Germany (by 2030)					
Evaluation of future importance					
Low importance	Low importance	Important	Important	Important	Important
Readiness to change opinion during the Delphi process					
+1/-4 - 3	+3/-4 -1	+1/-3 -2	+3/-5 - 2	+6/-4 +2	+2/-3 - 1

Figure 6-31: Evaluation of the expert panel answers on future role of biofuels and readiness to change the answer

The expert panel predicts petrol and diesel will have a long future (92% by 2020 and 78% by 2030). Engines will be increasingly hybridised (12% by 2020 and 30% by 2030) and the share of biofuels will increase (10% by 2020 and 15% by 2030). Biofuels were considered as a universal but limited fuel. Hydrogen will gain a share of 8% by 2030.

265 The following background information was provided: The EC targets using 20% of renewable energy in all economic sectors and 10% in the transport sector by 2020 and Directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for transport asks for a blending of a minimum of 5.75% renewables to petrol or diesel fuel.

Question 11: Development of segment shares (mean)[266]: The experts predicted an increasing segment of small cars such as Smart and Yaris (27% in 2008 to 35% in 2030). This is coherent with the predicted increase of BEVs, which are predominately used in light, small vehicles. This increase is at the expense of the lower and medium car segment and the "other vehicles" (SUVs, vans, utilities and sports cars), see table. The McKinsey study predicted that the segment of medium (e.g. Ford Focus) and upper-medium (e.g. Honda FCX) vehicles, which made 46% of the EU's vehicle production in 2008, will be the preferred market for FCVs. [McKinsey, 2010, p. 16] Experts comments were very different:

Vehicle segment	2008	2020	2030
a) Minis and small cars	26.8%	30.0%	35.0
b) Lower-medium class cars	42.5%	40.0%	38.5
c) Upper medium-upper class cars	5.3%	5.0%	5.0
d) others (SUVs, utilities, vans, sportcars etc.)	25.5%	23.5%	20.5

"This will be affected by alternative fuel development and fuel price. Segments will be shifted to more comfortable vehicles due to an aging population. No big changes expected. Company cars make a large share of the new registrations and will stay at least in the middle class segment in the future. Luxury segment will increase."

Question 12: Development of motorisation (mean)[267]: The experts predicted only a few changes in the future vehicle motorisation of newly registered cars. It was clearly mentioned that performance of electric vehicles cannot be compared to current vehicles and has to be thought anew. The comments were controversial: "*Relative low change in the structure. Trend of downsizing will not necessarily lead to a reduction of the performance. Incl. vehicles with boosters providing a higher performance only for a short-term period. Increase expected due to reduction of driving resistance (weight, cross-section area, drag factors). 51-90 kW will stay main range. Increase of the average performance. Technological progress will find new technologies such as hybridisation and new fuels but not on the costs of vehicle peak performance. Electrical drives need another sorting of the kW-classes, not comparable."*

	2008	2020	2030
up to 50 kW	6.9%	8.5%	10.8%
51-90 kW	45.7%	48.3%	49.2%
91-130 kW	34.5%	32.3%	31.0%
131 kW and more	12.9%	10.9%	8.9%

Question 13: Development of the share of centralised hydrogen production (mean): Hydrogen shall be produced mainly centrally, i.e. 76% central production by 2020 and 68% by 2030, indicating a diversification of H_2-production. Currently, no data is available. Several studies predict a centralisation of the H_2-production with a growing demand. However, the experts commenting in this direction also see a trend towards decentralised production. During the evaluation process, the mean changed only slightly from 69% to 68% centralised production. The experts commented on the questions as follows:

2020	76,4%
2030	68,1%

***Centralised production**: "2020: Probably from fossil fuel, but some large wind farm generation. 2030: more from large renewable energy installations. Economy of scale will be necessary as I don't think on-site conversion stands a chance economically. Mother-daughter stations will be the future. In small amounts as residuals from fuel production processes and – may be – for energy purposes. No business case – no estimation possible. Decentralised production at the filling station will be too expensive. For a better use of excess wind energy decentralised facilities are better."*

***Decentralised production**. Clearly this is fully dependent on the rate of development of alternative fuels. However, I firmly believe, once these come available at the price they will sell very well. The footprint of the conversion system plus fuelling station is WAY too large for normal urban applications."*

266 Data of 2008 from kba-statistics, table 1

267 Data of 2008 from kba-statistics, table 1

Question 14: Role of H_2-transport fuel production processes in Germany by 2030

Several options were suggested to the expert panel for H_2-fuel production. "*Electrolysis using renewable electricity from wind or solar energy being at the same time an energy storage medium*" (mean 4.4) was the only option which was evaluated as very important. *Natural gas reforming* (3.5) and the *use of H_2-residuals* (3.4) were evaluated as second and third best and particularly important during the transformation phase. *Electrolysis using conventional national electricity mix* (3.0) and *gasification using biomass* (2.8) were evaluated neutrally. Thermo-chemical processes (2.0) and electrolysis using electricity from coal power plants in combination with CCS (1.9) were evaluated as being of low importance. The two latter options were included in suggestions by experts from the first Delphi-round. The evaluation of the H_2-production processes changed little during the evaluation process. However, the experts' answers strongly reflected the need for H_2-production from renewable sources:

Natural gas by reforming: *"Large plants. Also with CCS."*

Electrolysis using conventional national electricity mix: *"Important during transition while proving technology. The pathway could leave fossil fuels."*

Electrolysis using renewable electricity from wind or solar energy being at the same time an energy storage medium: *"Ultimate goal. Option to use fluctuating energy from wind and solar. Only reasonable when excess renewable from wind is available. Use of excess wind energy, the amount of excess energy depends on the power plant structure. Direct coupling of the H_2-production to the wind park. Would be a very important production opportunity, but alternative a) & b) will dominate still in 20 years. Renewable electricity is the important panacea but once it's in the grid it can't be identified as 'renewable' except with the use of credits. If renewable electricity is successful in the long-term (and it likely will be) the concern will be mostly on the input side of the grid and no longer on the output side. People can say their H_2 is from renewable power but who will know unless it's used on-site and off-the-grid."*

Residue from chemical processes: *"Probably will continue to capture H_2 this way. Important during the transformation phase. Volume decreases due to process optimisation. Too expensive. Not enough capacity."*

a) Reforming of natural gas	b) Electrolysis from national electricity mix	c) Electrolysis, renewable wind, PV – incl. energy storage	d) Residual from chemical processes	e) Gasification or liquid reforming of biomass	f) Electrolysis, coal in combination with CCS	g) Thermo-chemical processes
Role of H_2-fuel production processes in Germany by 2030						
Evaluation of future importance						
Important	Neutral	Very important	Important / Neutral	Neutral	Low importance	Low importance
Readiness to change opinion during the Delphi process						
+2/-3 $\boxed{-1}$	+5/-5 $\boxed{+0}$	+3/-4 $\boxed{-1}$	+5/-6 $\boxed{-1}$	+0/-1 $\boxed{-1}$		

Figure 6-32: Evaluation of the expert panel answers on H_2-production options and readiness to change the answer

Gasification or liquid reforming of biomass: *"Will compete with biofuels for biomass. Too expensive and energy inefficient."*

Electrolysis using electricity from coal power plants in combination with CCS: *"It will not be possible to explain this to the population."*

In summary, only petrol (38%), diesel (40%) also used in hybrid vehicles (hybridisation share of 20%), BEVs (7.2%) and hydrogen (8%) reached relevant support by the expert panel. Biofuels (17%) had also a noteworthy share, but are mainly used as blends in conventional

ICEs. Thus, biofuels substitute conventional fuels; they use conventional propulsion technologies. In addition, biofuels could play a role for HDV application. However, the availability of biofuels for transport applications is seen as critical. CNG (3.3%) and LPG (2.5%) will play only a minor role. In the medium-term (2030) the experts foresee use of 8% hydrogen fuel for cars. It is best produced through electrolysis using renewable electricity, i.e. contributing also to an extension of a renewable energy system. Hybridisation will play a major role in the future. The share of BEVs corresponds with the assessment that vehicle motorisation and size will remain quite stable.

6.3.2.3 Period within which defined events or developments which influence the market introduction of hydrogen as a fuel will have occurred for the first time

The following eight questions were aimed at the analysis of a time frame within which important developments which may have the potential to influence the market introduction of H_2-fuel occur. The results are summarised in *Figure 6-33*. The answers are not linearly ranked, thus the median is the relevant evaluation criteria.

Thesis	2010	2015	2020	2025	>2030
16) Peak Oil is reached **between 2015 and 2019**		+1/-3 -2			
21) EU carbon trading costs reach 25 €/Mg CO_2 **between 2015 and 2019**		+0/-6 -6			
20a) Hybridisation of vehicles with spark ignition engine is maturely developed **between 2015 and 2019**		+2/-3 -1			
20b) Hybridisation of vehicles with compression ignition engine is maturely developed **between 2015 and 2019**		+6/-2 +4			
17) The average weekly all countries crude oil spot price weighted by estimated export volume reaches 200 USD/bbl **between 2020 and 2024**			+1/-6 -5		
19) One million BEVs are produced annually (worldwide) (at least 4 wheels, no wheel chairs etc.) **between 2020 and 2024**			+5/-9 -4		
20c) Heavy duty natural gas compression ignition engine technology is maturely developed **between 2020 and 2024**			+2/-4 -2		
23) Signif. number of large German cities closed urban centres for private vehicles or have a congestion charging system [...] **between 2020 and 2024**			+3/-5 -2		
20d) Spark-ignition-engine technology operated by an H_2-natural gas blend is maturely developed **2025**				+3/-4 -1	
18) One million FCVs are produced annually (worldwide) (at least 4 wheels, no wheel chairs etc.) **between 2025 and 2029**				+6/-4 +2	
22) CO_2 CCS technology is regularly applied in Germany **between 2025 and 2029**				+7/-2 +5	

Thesis	2010	2015	2020	2025	>2030
24) Green party platform issues dominate European politics, increasing the respective regulatory power **never**					+1/-5 -4

Figure 6-33: Expert panel evaluation (median) of first appearance of important events

Question 16: Peak oil is reached: Currently, new production technologies such as fracking are opening access to new resources. However, in the meantime even conservative organisations such as the IEA have assessed that peak oil has already happened or will happen soon (see section 3.6). Thus, it is hardly surprising that the assessment of the experts varied widely from ‘peak oil has already happened’ to ‘it will happen only after 2030’. The median of the answers determined peak oil to the period between 2015 and 2019. The evaluation of the topic was quite stable during the course of the analysis. Comments by experts on the topic included:

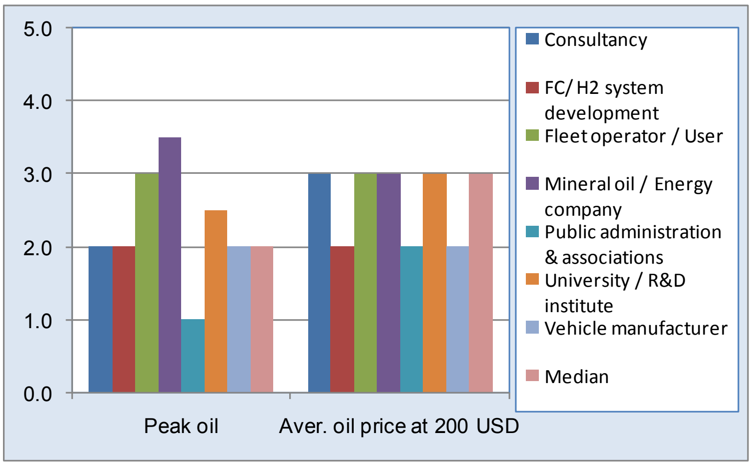


Figure 6-34: Sectoral comparison on timing of peak oil and oil price at 200 USD (1 = 2010-2014, 2 = 2015-2019; 3 = 2020-2024; 4 = 2025-2029; 5 = >2030)

“We assume, that peak oil already happened. The problem are not the limited oil resources but the limited production capacity. I think the peak will finally turn out to be a very long plateau. No serious information available. Substitution by non conventional oil. Happened already in 2006.“

The distribution of answers between the different stakeholder groups is quite interesting, (*Figure 6-34*). The ‘average’ representative of the energy industry assessed peak oil as happening only after 2025, but the ‘average’ representative from public organisations evaluated peak oil to happen between 2010 and 2014. Also, the fleet operators stated that peak oil will be well ahead (between 2020 and 2024), i.e. also well ahead of the lifetime of currently procured vehicles. All other groups voted close to the median.

Question 17: The average weekly crude oil spot price of all countries weighted by estimated export volume reaches 200 USD/bbl: the oil price will be an important influential factor for the market introduction of all non-oil based alternative fuels. It is the basic key driver in most studies on the market entry of alternative fuels, but the estimations used vary widely. The expert group was provided with historical information, i.e. the maximum oil price ever reached (July 2008) was 137 USD/bbl. During the Delphi process the oil price was about 80 USD/bbl. The expert group stated that an oil price of 200 USD/bbl would be reached between 2020 and 2024. In the course of the Delphi process the expert group pushed this date ahead. Analysis of the expert opinion according to sector did not reveal any striking results. Comments from the experts included:

“If the raw oil price will be that high for a long time, other energies will become competitive, the oil producers will ensure their sales and will avoid to cross “magic prices”, the level of the “magic price” is still unknown. Prices will inevitably increase with decreasing resources, in the case of wars even faster. Speculation and economic factors make the oil price highly volatile. The trend of the oil price is increasing, but as a consequence of the financial crisis the globally available amount of money increased.”

Question 18/19: One million FCVs/BEVs are produced annually (worldwide) (at least 4 wheels, no wheelchairs etc.): The expert group was questioned about the market development of the two currently most competitive alternative fuel technologies, i.e. FCVs and BEVs. Points of interest included:

	FCVs	BEVs
The magic production number of M1 vehicles p.a. is reached between	2025-2030	2020-2024
Which is the country/region leading the technology development?	Europe	China
Which is the largest producing country/region?	Japan	China
Which is the country/region with the largest market?	Europe	China

Notably, Korea was not included in the questionnaire and it currently seems that the expert who commented “do not forget Korea” was making a point. The expert panel estimated that the first million four wheeled BEVs will be produced between 2020 and 2024. The first million four-wheeled FCVs shall be produced between 2025 and 2029, i.e. approximately five years later. Thus, the experts did not follow the public statements on a fast market penetration of FCVs. During the Delphi process, the magic M1 production date was postponed for BEVs and slightly pulled forward for FCVs. Interestingly, the deviation of data on BEVs is low: 50% of answers are “between 2020 and 2025”. 50% of answers on FCV implementation are in a 10-year range “between 2020 and 2030”. The experts’ statements on technology, markets and production leaders were quite clear:

The leading countries/regions for **technology development** shall be for:

- **FCVs**: Europe (55%), followed by Japan (21%), USA (15%) and China (9%).
- **BEVs**: China (63%), followed by Japan (22%), Europe (13%) and USA (3%).

The countries/regions leading in **technology and production capabilities** shall be for:

- **FCVs**: Japan (41%) and Europe (38%) followed by China (19%) and the USA (3%).
- **BEVs**: China (73%), followed at a large distance by Japan (12%), Europe (6%), India (6%) and USA (3%).

The Delphi process was run in the middle of the automotive crisis which hit the US car manufacturers very hard. This may explain the limited trust of the experts in the capacity of the US-industry in FCV- and BEV-technology. However, at least for BEVs the reality is different: US-manufacturers offer manifold models. Tesla (not GM or Ford) is one of the world technology leaders. The leading **market** countries/regions shall be for:

- **FCVs**: Europe (36%), followed by China (32%), USA (21%) and Japan (11%) which is lagging behind, but only has a small population (M127) compared with Europe and China.
- **BEVs**: China (83%), followed by Europe (10%), USA and India, both 3%. China is by far the largest vehicle market; it became the first market to sell more than M20 vehicles p.a. in 2013 (USA: M15.6).[268]

China was evaluated as the clear BEV-technology, production and market leader. Even India was given a role on BEV-production and as a market. The traditional automotive regions are clearly lagging behind according to the opinion of the expert panel. However, in 2011 Chinese Prime Minister Wen personally remarked on the automotive future of China. He was sceptical about whether BEVs would be able to be established on the market at all. After

[268] http://www.cbsnews.com/news/china-breaks-world-record-for-car-sales-in-2013/; 07.02.2014

several Chinese electrical vehicle producers could not fulfil their production plans, he said that the development of BEV technology has just started.[269] Experts commented as follows:

a) H_2FC-technology development leading country is ...: *"This is difficult - probably put my money on the Japanese - but would say they are all equal at the moment. Do not forget Korea. Because FCs will be a rare application for cars, the answering of this question does not make much sense, this will be different for special markets such as military or space. If large amounts of H_2 have to be placed. China has currently the most patents in this R&D field."*

a) BEV-technology development leading country is ...: *"Answer does not include PHEVs. The co-operations are global, synergies between the OEMs."*

b) Most of BEVs is manufactured in ...: *"so-called Neighbourhood EV for about 5 k€/car."*

c) Most important H_2FC market is ...: *Mainly because they (US) are rich and are more likely to afford them. There is currently no sales market, but it will be China, because a lot of money is available and the prestige thinking is high."*

c) Most important BEV market is...: *"This is because these countries (China) have an imperative to clean up the air in their cities - and battery electric cars are most likely to be available for short range city driving in the medium term. If BEVs will finally enter the market at all, it will happen in China, where else with a quarter of the global population."*

The introduction of H_2FCVs is very limited to date: several hundred demonstration vehicles (cars, buses) and just over 200 fuelling stations are active worldwide (120 of them in the EU), with over 100 more in the planning stage.[270]

ZSW recently determined the number of electric cars in use world-wide. Nearly k100 electric cars were on the road in early 2012, in 2013 the vehicle count came to k200 and already reached k405 early 2014. If the past three years' growth rates are sustained, then more than one million EVs will be sold worldwide as early as the beginning of 2016. [ZSW, 2014]

In 2009, BCG predicted in its steady pace scenario that Western Europe would be the largest BEV market (M0.6 units) followed by Northern America (M0.4 units), Japan (M0.3 units) and China (M0.2 units). However, Northern America would be, by far, the largest market (48% of global sales) for HEVs and REVs (M6 units). 18% of city cars across the four regions would be BEVs. [Dinger, 2010, p. 7; Book, 2009, p. 7-8] A breakdown in global BEVs stocks shows that the United States (38%, k71) had by far the biggest EV stock in 2012, followed by Japan (24%), France (11%), China (6%), UK (4%), Netherlands (4%) and Germany (3%). [IEA, 2013 (1), p. 4, 8] Many countries follow national plans to support the diffusion of electric vehicles (BEVs, PHEVs, REVs and HEVs). However, only the US government plans seem to be realistic. The Chinese government just announced a programme concentrating on clean air and renewable energies which could change the situation in the centralised economy. The plans to install are as follows

China:	M5 EVs and M10 charging points by 2020, (Sales 2012: BEVs: k11, HEVs: k1.3, forecast 2017: k275),[271]
France:	M2 EVs by 2020, (BEV sales 2013: k14),
Germany:	M1 EVs by 2020, (New registrations 2013: BEVs: k6, HEVs: k26) [kba, fz13],
Spain:	M2.5 EVs by 2020,
UK:	M1.55 EVs by 2020,[272]
US:	M1 EVs by 2015, (New registr., 2013: BEVs: k48, HEVs: k496, PHEVs: k49).[273]

269 http://www.derwesten.de/auto/china-bremst-euphorie-fuer-elektroautos-id5000426.html; 16.09.2013

270 http://www.eubusiness.com/topics/energy/clean-power; 13.02.2013

271 http://evworld.com/news.cfm?newsid=30769; 16.09.2013

272 http://www.evsroll.com/Electric_Vehicle_Sales.html; 07.02.2014

273 http://electricdrive.org/index.php?ht=d/sp/i/20952/pid/20952; 16.09.2013

Question 20: the following new technologies have been maturely technologically developed. There are several technologies that may compete with FCVs for establishment on the market. The experts were asked to assess the timing of technology maturity of four technologies. Experts voted quite clearly for an imminent maturing of *HEVs with spark ignition* around 2015. This is supported by the design of current DOE HEV development targets, which target cost reductions and no longer includes technology development targets. A maturing of *diesel HEV technology* was foreseen between 2015 and 2019. This option was clearly better evaluated in the second Delphi-round. First models, such as the Peugeot 3008 Hybrid4, have been available on the market since 2011.

HDV gas compression ignition engines were determined for maturity after 2020, the *blending of CH_4-H_2* could be introduced around 2020. However, the comments and five, respectively nine, "never" votes showed that not all experts believed in the establishment of the two latter technologies. Experts commented as follows on the technology options:

Hybridisation of vehicles with spark ignition engine: "*Parallel hybridisation of ICEs."*

Hybridisation of vehicles with compression ignition engine: *"But too expensive."*

Heavy duty natural gas compression ignition engine: *"For what benefit, cannot evaluate preferences of the OEMs. Compression ignition must be dual fuel."*

Spark-ignition-engine operated by a hydrogen-natural gas blend: *"Seems not to be an option with potential. Technology is essential the same. H_2-CH_4 blends will never be popular over CH_4 alone."*

Questions 21: EU carbon trading costs reaches 25 €/Mg CO_2 *(Assumption: including only current group of emitters):* The cost of carbon emission rights will strongly influence the market introduction of any technology depending on renewable fuels. It is also an important question for ensuring a macro-economic sound management of climate change mitigation between the different sectors. Cost-benefit analysis of the EU regularly estimated a carbon price around 20 €/Mg CO_2, but current costs are down due to a growing surplus of allowances undermining the orderly functioning of the carbon market (see *Figure 3-4*). The experts were provided with the 2010 EUA costs of circa 13 €/Mg CO_2 for the evaluation of the question. Experts commented as follows:

"This depends on the future structure of the ETS, in particular, which sectors will be added in addition to the current selected stationary plants, today transport is not included. The ETS is based on shortening of the number of certificates and optimisation of processes. The market will regulate that the carbon price will not become too costly by shifting production or optimisation."

69% of experts voted for achievement of a carbon price higher than 25 €/Mg "between 2010 and 2014", see section 3.6 for a comparison with other scenarios. From the 2010 point of view, this development seemed to be in range after a recovery from the financial crisis. In any case, experts postponed the date significantly during the Delphi process.

Question 22: CO_2-CCS technology is regularly applied in Germany: only one expert saw CCS coming "between 2015 and 2019", but 36% voted that it will never become reality. If becoming reality at all, the experts planned for "between 2025 and 2029". However, the date was pulled closer during the course of the Delphi study. In the EC's RS_{2013} CCS would only develop after 2030, reaching a capacity of 38 GW only by 2050. [EC, DG Energy et.al., 2010, p. 29; 2013, p. 45] However, if the EC were to omit CCS fully from the calculation, the compliance gap to its CO_2-targets would increase even more. The experts commented:

"Lacking public acceptance in Germany. Not at large, meaningful scale. Country-by-country applications based on geological constraints, economics and competing technologies. If storage is possible from a geological and technical point of view. It does not work technically (beyond of prototypes) and will not work in the next 50 years. Then it would be superfluous due to alternatives."

Question 23: "A significant number of large German cities have closed their urban centres for private vehicles or have installed a congestion charging system to control car entry": in urban areas private car ownership is not conditional for mobility. The urban population suffers from air pollution and, in particular, noise, thus closing city centres to private cars is regularly discussed. The experts' comments differed widely between concrete belief in the scenario and total refusal of the imagination. Nonetheless, asked about the timing, the median of the groups' answers was located "between 2020 and 2024". The opinion of the expert panel did not change much during the course of the Delphi analysis. The experts commented as follows:

"It started already with environmental zones. Related to Germany, other countries have other problems and solutions. No need, the problem of climate change will not have the potential to interfere such strictly to people's lifestyle, it is rather ignored (re-election of the politicians)."

Some experts complained about the level of interference with people's privacy, but current scenarios on the future of the cities are going much further than closing cities to private cars. The Fraunhofer Institute recently developed a roadmap on the electro-mobile city. It suggests a linking of cities and electro-mobility on a systemic level. Future urban transport shall be fully electrified; car sharing shall be extended to all vehicles which are even interlinked.[274]

Question 24: "Green party platform issues dominate European politics, increasing the respective regulatory power": none of the experts expected that this would happen soon and 53% of the experts even expected that this would never happen. Experts commented that green policies and deduced regulations would be more likely to "infiltrate" the programmes of the established parties than becoming an independent aspect of European policy. This would happen in particular if green topics were to gain more economic influence, e.g. through the energy policy. The recent establishment of a German Ministry of Economic Affairs and Energy headed by the SPD Party Chairman, which identifies the Energiewende as one of its key issues, confirms these comments:

"Established parties will change their programmes in the case a „green movement“ becomes stronger to ensure their position. All parties will become different shades of 'green' and the so-called 'green' parties will remain radical by comparison and, as such, usually a minority. "Conventional" parties will see the economic benefit of a „green“ policy and will make attempts to keep their voters. Green parties are too inconvenient for the consumers. ... but the traditional parties will become more and more green. Rather the conservative parties will represent green topics, the green parties will become superfluous in the future. A one-topic party will not be successful in a democratic system in the long-term. Many green ideas and concepts are already common property. Green topics receive an increasing energy and economical political meaning, e.g. by reducing the fossil energy imports."

In summary, experts expected that peak oil and carbon trading costs of 25 €/Mg would be achieved between 2015-2019; an average weekly crude oil spot price over 200 USD/bbl would be achieved between 2020-2024 and CCS could be regularly applied by 2029, (if at all). These circumstances indicate a further increase in the costs of fossil fuel based energy. Hybridised petrol cars shall be maturely developed before 2020, the first million BEVs produced between 2020-2024 and the first million FCVs between 2025-2029. Thus, the technological basis for further regulatory measures beyond 95 gCO_2/km would be available. Even if it is not expected that green parties will come into power, green policy aspects will further infiltrate the programmes of established parties as long as it is for their benefit.

274 Fraunhofer-Institut IAO, Stuttgart 2011, p. 9

6.3.2.4 Level of agreement on specific theses which are influencing the marketing process of hydrogen fuel

In the third section the experts were provided with 11 theses and were asked for their degree of agreement using a scale of five levels. The results are summarised in *Figure 6-35* showing median, mean and the readiness to change.

"By 2030, in the EU, in particular in Germany …"	Me-dian	Mean	Result	Readiness to change
27) In the future strict government standards (incl. a rise in CO_2-emissions costs) are the most important tool against climate change	4	4.3	agree	+3/0 +3
26) In the future innovative technologies are the most important tool against climate change	4	4.1	agree	+0/-2 -2
31) In the future sustainable products and services provide significant share (>10%) to the national GDP	4	4.1	agree	+0/-2 -2
25) Car will stay the most important passenger transport means	4	4.0	agree	+1/-2 -1
32) Emerging countries undergo change in consciousness and policy supporting environment and climate change measures	4	3.7	agree	+3/-2 +1
28) In future consumer behaviour is guided by [..] sustainable development & environmental awareness. Company's Corporate Social Responsibility are important to its success	4	3.6	agree	+6/-1 +5
29) Costs of environmental protection measures and use of resources increase dramatically and have an increasingly negative effect on companies' profits	4	3.6	agree	+7/-2 +5
33) In the future emerging economies skip some innovation/ technology levels and enter directly in advanced technologies reducing their CO_2-emissions	4	3.6	agree	+2/-4 -2
35) In the future large infrastructure projects - e.g. H_2-/BEVs, infrastructure - are mainly privately financed	3	3.2	neutral	+8/-2 +6
34) In the future alternative urban freight transport systems are implemented, e.g. tube systems, distribution centres etc.	3	3.1	neutral	+2/-4 -2
30) Customers are ready to pay a premium for "green" products and services of up to 20%	3	3.0	neutral	+3/-4 -1

Figure 6-35: Agreement with 11 theses describing framework conditions of H_2-fuel introduction

Thesis 25: By 2030, in the EU, in particular in Germany, …the **car will remain the most important passenger transport means**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*0%*	*22%*	*53%*	*25%*

The experts confirmed that the car would remain the main passenger transport means. Thereby, individual transport will remain a significant CO_2-source as long as fossil fuels are used. 78% of experts at least agreed with this thesis, the other 22% were neutral and no one contradicted the statement. During the Delphi process the readiness of the experts to change their opinion was very low. Experts commented as follows on this statement:

„Battery bicycle, public transport. Mixture, plurality. Depends if it is a rural or urban area."

This statement is confirmed by the Shell car study which assumes a more or less stable share of passenger cars in the modal split of 84%. [Shell, 2009, p. 29] However, other studies assume a shifting away from the private car by 2030:

"*While, in the past, the car has been the "favourite baby", the future use of the car is much more pragmatic. The car is not any more regarded to be a way to express the owner's personality, but its functional reasons are becoming much more important. The more rational view on the car facilitates the switch over to other modes of transport if they are better suited for the respective purpose. Thus, in rural areas the status of the car will be much more important as in urban areas, where environmental zones, limited and expensive parking places and other transport management means promote the use of public transport." [Ifmo, 2002, p. 42]*

Thesis 26: By 2030, in the EU, in particular in Germany … **innovative technologies are the most important tool against climate change**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*9%*	*12%*	*39%*	*39%*

79% of experts agreed or strongly agreed that the availability of advanced technologies could be the most powerful tool for protecting the climate. Only 12% were neutral and 9% disagreed. Thus, nearly 80% agreement was reached from experts mainly representing engineers and natural scientists. Again, there was not much change in the answers during the Delphi process. Experts' comments included:

"Innovations are driven by increased regulation. Change in consumption behaviour is more effective and cheaper with the same potential. Energy saving, change of behaviour. If it is used for increased savings."

Thesis 27: By 2030, in the EU, in particular in Germany … **strict governmental standards (incl. all rise in costs of CO_2-emissions) are the most important tool against climate change**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*0%*	*6%*	*59%*	*34%*

No expert disagreed with the thesis that government standards could be the key to protecting the climate. 6% were neutral, but 94% agreed or even strongly agreed with this thesis. This statement included the use of dedicated taxes. Again, there was not much change in the answers during the Delphi process.

*„Comprehension seems to be unrealistic. If the politicians would be ready to implement this. Only a **changed mindset of the population and voluntary limitations of the personal freedom will result in a** changed mobility behaviour. In general this works with financial pressure. Consumers normally react on this measure or an increase of prices."*

Thesis 28: By 2030, in the EU, in particular in Germany… **consumer behaviour is guided by the concept of sustainable development and environ-mental consciousness. Company's Corporate Social Responsibilities will become important to a company's success.**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	3%	*3%*	*33%*	*55%*	*6%*

Only 6% of experts disagreed that environmental consciousness and company's responsibility could support climate protection. 61% at least agreed and 33% had a neutral opinion towards the concept of responsibility. This is less support than for the availability of technologies or governmental interference, but it is only a "soft measure". In any case, this is an important statement, because the FCV premium price shall be justified using, inter alia, the marketing instrument of image building. During the course of the Delphi study support for this statement increased. In the second Delphi round sustainability was defined according to the Brundtland report, see section 6.3.1. Experts commented on the question as follows:

„The consumers are at least 90% price orientated; there is no reason to hope that this will change, second half of the sentence is ok. Only in the case if no limitation has to be expected, sustainability and environmental protection are no "life maxims" but "lived" when it is suitable. As always: it depends …. Social responsibility and other sustainability strategies are already today a decisive factor for the assessment of market-listed companies and have a positive influence on the share value."

A leading German logistic trade journal analysed the factors that constitute the image of a company by questioning 400 enterprises. The factor "Compliance with legal and moral basic principles" was included for the first time and managed to gain the fourth place. Environmental orientation and innovation were ranked fifth and sixth.

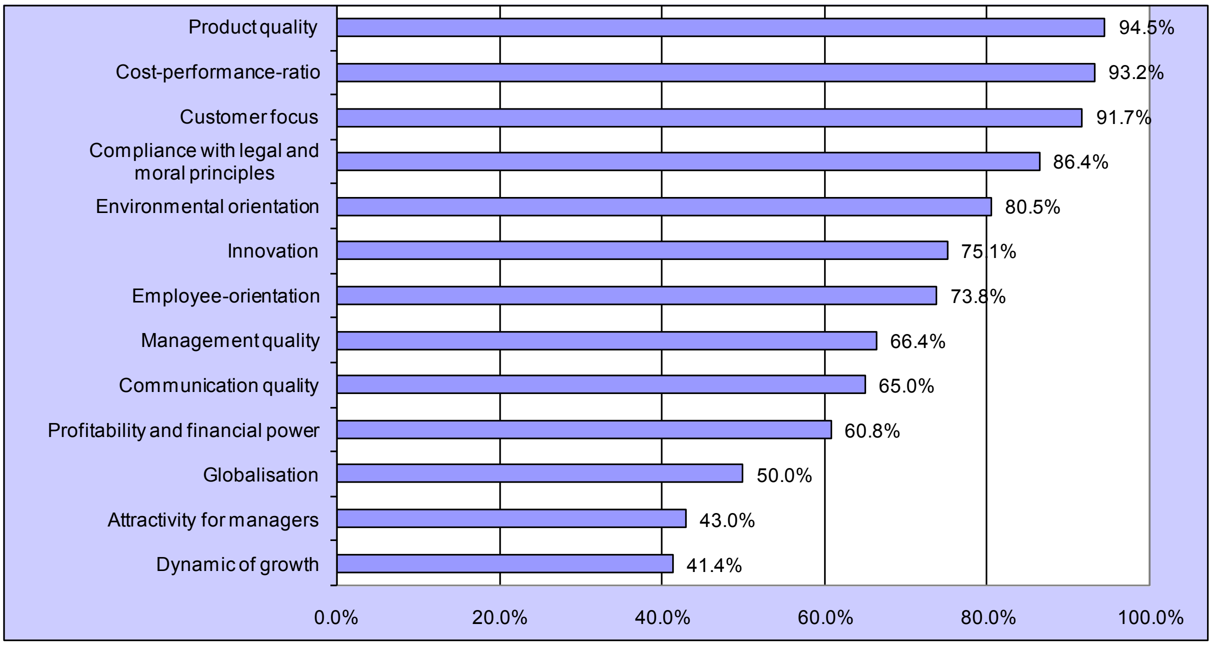


Figure 6-36: Factors for Image Creation of an enterprise [Bauer, 2011, p. 22]

Thesis 29: By 2030, in the EU, in particular in Germany ... **costs of environmental protection measures and use of resources are increasing dramatically and have an increasingly negative effect on companies' profits**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*9%*	*33%*	*48%*	*9%*

9% of experts disagreed that environmental costs are increasingly affecting the business in a negative way, 33% were neutral and 58% agreed or strongly agreed. During the course of the Delphi study agreement on this statement increased further. Comments from experts included:

"It is possible to earn money with environmental protection. Politician will not dare to ask consumers to cover external costs, this will have to be paid by the society as a whole. I think the industry will know how to avoid a too high disturbance."

Thesis 30: By 2030, in the EU, in particular in Germany … **customers are ready to pay a premium for "green" products and services of up to 20%**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	6%	*29%*	*32%*	*21%*	*12%*

35% of experts disagreed with this statement, another 32% were neutral and 33% of the experts (strongly) agreed. Only a few changes occurred in the answers of the experts during the course of the Delphi-analysis. This topic was heavily commented on by the experts:

„All recent efforts of the industry to sell ecological vehicles with a premium price failed (VW Lupo 3l; Audi A2 TDI/ Audi Duo etc. etc.). Consumers delegate the responsibility to the industry and are not ready to pay for any higher costs, this is in contrast to the results of many polls. In Germany, with a suitable marketing effort. According to polls a high percentage is ready, but if it comes to implementation, there is not a lot of result. Depends on the basic price (20% of 1 € is different to 20% of 20 k€) and on the related marketing strategy. Readiness to pay is very low, only in connection with a respective "benefit", e.g. exemption from city road charge. Acceptance depends mainly on the use of the income and how transparent the use takes place. I think pressure has to come from the consumer, not from the industry."

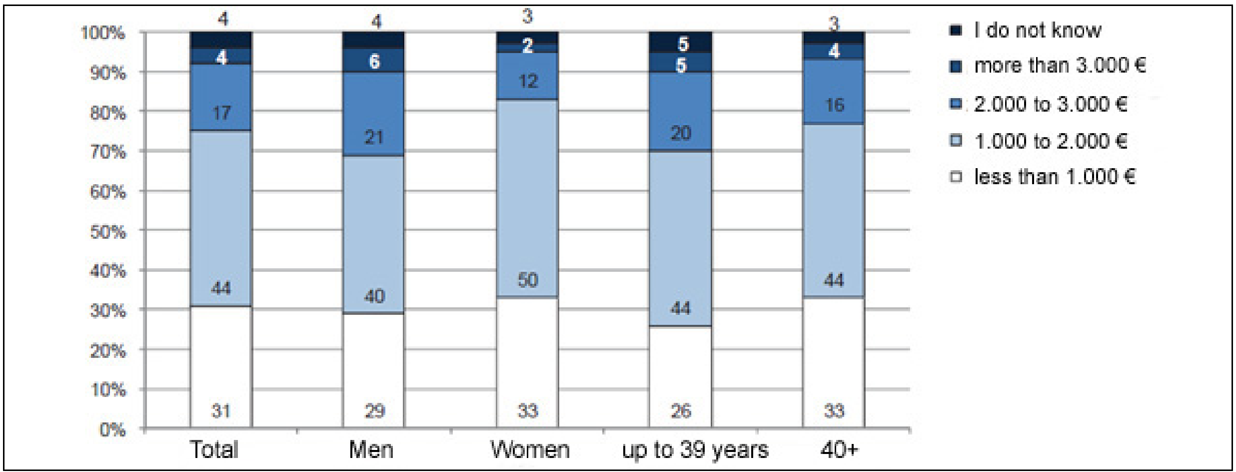


Figure 6-37: Would you, in principal, be prepared to pay a premium for an environmentally sustainable system compared to a convention propulsion system? [Diez et.al., 2010, p. 18]

Several studies investigated the readiness to pay. The German Institute for Automotive Industry investigated buying decisions: 22.8% of the interviewees saw ecology as a **motivation factor**, i.e. they would buy a vehicle with a maximum environmental sustainability and would be ready to trade-off other product characteristics (e.g. performance, comfort). The other 77.2% saw ecology as a **hygienic factor**; they would buy a vehicle with optimal performance and high comfort, but expect the environmental requirements to be appropriately covered. [Diez et.al., 2010, p. 17] These results support the scepticism of the experts. A study by Aral investigated how much people would be ready to pay as a premium for an environmentally green, sustainable propulsion system, (*Figure 6-37*). 69% of people would be prepared to pay at least an extra 1-2 k€. Plötz et.al. assume a much higher willingness to pay, e.g. about 50% would be willing to pay at least 10% extra. [Plötz, 2013, p. 18]

Thesis 31: By 2030, in the EU, in particular in Germany … **sustain. products and services provide significant share (>10%) of the national GDP**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*3%*	*3%*	*71%*	*24%*

Only 3% of the experts disagreed with this thesis, another 3% were neutral, but 94% agreed. Assessment of this thesis remained almost constant during the course of the Delphi study. There were no comments by the experts on this topic. The German State and the economy spend around 1.3% of GNP on direct environmental tasks (e.g. investment in and operation of waste water plants), this was about 32.9 G€ in 2008.[275]

[275] http://www.umweltbundesamt.de/daten/; 15.11.2015

Thesis 32: By 2030 … **emerging countries undergo change in consciousness and policy supporting environmental and climate change measures**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*9%*	*19%*	*66%*	*6%*

9% of experts were in dissent with this thesis, 19% were neutral and 72% agreed. There were only a few changes in the answers of the experts during the course of the Delphi-analysis. Experts commented as follows:

"No change in consciousness but linking support to development and environmental protection would give the right incentives (industrialised countries would buy a good consciousness through support to emerging and developing countries)."

Thesis 33: By 2030, … **emerging economies skip some innovation/technology levels and enter directly into advanced technologies reducing their CO_2-emissions**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*15%*	*24%*	*44%*	*18%*

15% of the experts disagreed with this thesis, 24% were neutral and 61% agreed. There was not much change in the answers of the experts during the course of the Delphi-analysis. Comments by the experts were:

„This has to be supported by the industrialised countries. Not for this reason, but because no serious person would use the technology of the day before yesterday, if he could get yesterday's/today's one. Look at China, but not for environmental but power purposes."

Thesis 34: By 2030, in the EU, in particular in Germany … **alternative urban freight transport systems are implemented, e.g. tube systems, joint company distribution centres etc.**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	6%	*12%*	*47%*	*35%*	*0%*

18% of the experts disagreed with this thesis, 47% were neutral and 35% agreed, but no expert strongly agreed. The evaluation of this thesis increased significantly during the course of the Delphi-Analysis. The experts commented as follows on this question:

„Distribution centres already exist, I am sceptical against tube systems. Zero emission distribution vehicles."

Many cities run electro-mobility pilot projects to demonstrate the synergies of local distribution centres and electric vehicles, examples include courier-messenger-parcel services which are also demonstrated in the Berlin International Showcase for Electromobility.

Thesis 35: By 2030, in the EU, in particular in Germany … **large infrastructure projects - e.g. H_2-infrastructure, recharging points for electric vehicles, streets - are mainly privately financed**	*strongly disagree*	*dis-agree*	*neutral*	*agree*	*strongly agree*
	0%	*15%*	*53%*	*32%*	*0%*

15% of the experts disagreed with this thesis, but 53% were neutral and 32% agreed. It is expected that the H_2-infrastructure would be built and financed by the mineral oil, energy and gas industry but subsidised (guarantees, tax reduction, direct subsidies) by the government in Germany. Experts commented as follows on this thesis:

„It is necessary to share the risk: investments promise only long-term return on capital. Public implementation because targets of the society are followed. The State will be involved significantly at least indirectly (guarantees, tax reductions, subsidies). The current little success is against it in Germany (Warnowtunnel). Unthinkable without public support, because financial risks are too large (Transrapid!). Perhaps direct private financing, but if analysed in a transparent way it is a public

financing (subsidies, tax reductions etc). Large level of private financing if used decentrally (charging point in the garage)."

In summary, expert agreement with the eleven theses on circumstances which could promote the market introduction was mainly positive. Experts firmly agreed that strict government standards (including all measures which would increase the costs of CO_2-emissions) will be the most important tool against climate change in the future. However, technological progress would also be induced through economic interests of the industry as experts highly agreed that sustainable products and services would provide a significant share (>10%) of the national GDP by 2030. Innovative technologies could become an important tool against climate change according to the expert panel. Even more, the expert panel agreed that environmental protection costs and the increasing costs for the use of resources will have a negative effect on companies' profits. Future consumer behaviour is believed to be guided increasingly by sustainability aspects and a company's corporate social responsibility will become more important to a company's success. However, the experts remained sceptic as to whether the customers would be willing to pay more (i.e. of up to 20%) for green products. For a mid-class vehicle this would be about 4-6 k€.

6.3.2.5 Importance, urgency and feasibility of defined short to long-term actions to further promote the market introduction of hydrogen fuel

In a last step, the experts were asked which short-to-long-term H_2-fuel market introduction promotion measures they would evaluate as important, urgent and feasible. These answers are described in the following in accordance to their ranking on importance. Six measures were evaluated as 'very important'; three of these were evaluated as 'fully feasible'; two 'feasible' and one 'neutral'. All suggested measures were evaluated as realisable in the midterm according to the expert panel. These measures include:

Implementation of standards (Question 36), this activity is well on the way and is pursued by international, regional and national organisations, (see section 3.4). The evaluation of the significance of this topic increased during the course of the Delphi study. Experts commented on this measure as follows:

"Precondition for this question is that the market introduction of H_2-fuel is evaluated as important at all, I would contradict this assessment, thus answers are made under this reservation. Already being done at UN ECE level. This is an on-going process as technologies evolve. Missing standards are a constraining factor already today."

Training of existing and new maintenance and repair staff as well as service staff (Questions 46&47) were the second and third best evaluated measures. Experience from the market introduction of NGVs and the first marketing activities for BEVs shows that this is a very important topic which needs a long preparation time, in particular as FCVs combine several knowledge areas, i.e. working with explosive gases under high pressure, working with high voltage and working with electro-chemical processes. The assessment of importance and feasibility of dedicated technical staff training increased strongly during the course of the project. The **training of sales personnel** to better market FCVs among conventional vehicles was evaluated as important in the midterm and as feasible (Question 48). Comments on training needs included:

***Training of technical staff**: "This is a particularly important issue as the "lead time" to have sufficient and sufficiently trained technical and operating staff can be as long as 10 years. Does not work in another way. However, in my opinion, there will be a selling of mobility not of the vehicle in the future. Not own personnel, but absolutely the staff of the garages of the manufacturers. Not only mechanical electricians, also mechanical and electrical engineers. Start of education until 2015. Depends upon* *market penetration rates. If the vehicles will be freely available. Should start in 2015, thus effective in (about) 2018. Long lead times of educational changes. Gas AND Electricity!"*

***Training of sales staff**: "First the technology has to work steadily and needs to be distributed. I guess if OEM's need the pull of markets this is important."*

Public co-financing of the introduction of H_2-fuel was also evaluated as being of high importance by the experts, again a midterm urgency was selected, but a concrete **tax exemption of H_2-fuel for at least 10 years or public co-funding of H_2-infrastructure beyond the first demonstration projects** (Questions 37&39) were evaluated as only "feasible" by the expert panel. Importance, urgency and feasibility were rated higher in the second round of the Delphi-study. Experts preferred to stimulate H_2-demand by supporting the fuel price or FCVs, rather than the infrastructure construction. However, **financial support for the production of renewable hydrogen** and **direct subsidies to fleet and private FCV purchasers**, e.g. 5 k€/car (new Question 52&38) were only evaluated as "important", neutral urgency and feasibility. For example, national support for buying a BEV is: China: 6.5 k€ and Spain: 6 k€ etc. [IEA, 2013 (1), p. 20] Several experts suggested an "H_2-cent", thus it was added to the questionnaire in the second round (Question 51), but the evaluation of the whole panel was neutral. Experts commented as follows on subsidies:

***Tax reduction**: "As soon as H_2 reaches a significant market share, a tax reduction is not anymore possible. Solidarity with the State losses by e.g. "Eco-cent" on conventional fuels. Facing the exorbitant technically caused costs for H_2, taxes are a relatively irrelevant cost factor. Signalling, if it is really wanted. As it will be relevant only for a small number of vehicles, the financial minister will not be very reluctant. In a first phase only at project level, no market. A realistic cost-/subsidy-concept needs to be elaborated, because with a large scale, H_2-production costs will decline significantly, e.g. introduction of a cost cap (the incentive for a real cost reduction needs to maintain). The exemption covers the period 2020 to 2030. Important if government and stakeholders put commercial H_2 as a priority, which I don't think they will. But it is important for the overall, long term success. A binding perspective would be sufficient, this could include a coupling to the mineral oil price (or fixed difference to conventional fuels). Real market introduction programmes would be more efficient."*

***Support to infrastructure**: "Should depend on the CO_2-balance of the production pathway. Financed with an Eco-cent. This could result into a waste of money and should be carefully considered in accordance with a possible economic operation of the infrastructure. If the price of H_2 would be good and sales would be stimulated, the construction of an infrastructure should be profitable for the operator without any subsidies. Depends on political priority. It's not happening without strong government support. Never any urgency. I agree with the majority but think that primarily the H_2-price has to be attractive and that demand has to be stimulated through the number of vehicles."*

***Support to renewable H_2**: Could be helpful in the beginning, but risk of wrong allocation as with all governmental subsidies. Important when large fleets start operation. Question of priority compared to a support to demand. Reasonable for all renewable energy pathways in the transport sector, singular subsidies for H_2 would cause a problem of acceptance ("H_2-compulsory levy"). "Transparency and kind of usage of the income would be important for the acceptance."*

***Direct subsidy to FCV buyers**: "In the medium-long term this should be entirely possible although maybe less necessary as price of oil goes up steeply. Important during the next 10 years, afterwards not anymore important. 5 k€ will not be enough. Earlier only for specific fleets. Only few vehicles, no reluctance of the financial minister expected. The technology has to convince potential customers without any subsidy, but buy for image reasons. Probably direct subsidies when the wide market should buy. Support to operators is the key for a successful market introduction, see wind energy during the 1990ties. Successfully implemented in the USA. See success of the German car scrap bonus. At the moment rather for electric vehicles – subsidies need to be developed in parallel to the development of the infrastructure. EU wide implementation when the FCVs will be available."*

***H_2-cent**: "All CO_2-neutral fuels will have to be treated in the same way. Development money is important but I wonder about the practicability of this. Subsidies are always arguable. As long as the regulation for the 'Coal-cent' are not finally clarified, this should be not in the focus. A cost-benefit analysis could evaluate the implementation. The acceptance is arguable, electricity is already more expensive due to the use of photovoltaic. It is problematic to introduce such a drastic measure for one technology, better: support to sustainability. If, then fast start. The fuel industries would not stand for it.*

Not in these economic times. Reasonable for the use of all renewable energy carriers in the transport sector, singular subsidies to H_2 would create an H_2-acceptance problem."

Also, the request for agreement and compliance with international mandatory **CO_2-reduction targets beyond the 'Kyoto-protocol'** was evaluated as important (Question 43). The evaluation of urgency and importance increased in the second Delphi-round probably due to the approaching of the terminal date of the Kyoto-protocol; feasibility was evaluated less. In the meantime new targets have been agreed, see section 3.1.

"Feel very pessimistic about this - really believe it could be the cause of major world conflict eventually. Kyoto does not work; paper tiger. 'Urgent' seemed to be too optimistic."

The experts were also asked to evaluate regulatory measures such as the further tightening of the **EU car fleet standard** from 130 gCO_2/km in 2012 and 95 gCO_2/km in 2020 to e.g. 75 gCO_2/km in 2030 (Question 40), the **inclusion of transport into the EU Emission Trading Scheme** (Question 41) or the introduction of a strong **CO_2-component to the tax concessions granted for company cars** (Question 44). All measures were evaluated as important in the mid-term and feasible. The feasibility of stricter fleet standards was evaluated much better during the second Delphi-round. (The EU Parliament voted for '68-75 g CO_2/km by 2025' in 2013).[276] However, the option to include transport in the ETS was postponed during the Delphi-course. The evaluation on the taxation of company cars did not change much during the course of the analysis. Experts commented on the measures as follows:

***Fleet standard**: "The mileage and the specific consumption will probably be reduced in the EU in the future. If the target would still be implemented, the industry needs 15 years to comply. From today's point of view only feasible with a lighter and smaller average fleet, probably negative consequences for the passive vehicle safety. Not relevant, image is more important than strict regulation (OEMs understood the market); ...if feasible. Auto industry will stall and resist, as always. The industry will gain clarity on future development targets and is forced to act. The targets have to be defined early, if compliance will be feasible, this is another question. Now in the law: CO_2 and cars."*

***Inclusion to ETS**: "There are other alternative policies. ...if feasible. I cannot evaluate this, but surely, it would be not easy to regulate. If it is really wanted (perhaps problems with HDV-transit countries in the EU). Earlier would be not realistic. The fuel production has to be included, fleet limits or similar measures are not the right measures. I would have thought that the measuring of carbon output etc. would be fairly hard to implement."*

***Taxation of commercial vehicles**: "Starting with commercial vehicles is a great way to go. Best would be to couple the tax deductibility to a maximum CO_2-emission (above the limit, no tax granting anymore). It would be better to "punish" the CO_2-emmissions of the vehicle by a taxation of the fuel, no fuel consumption, no costs!"*

Another five measures were related to marketing and public relation measures. The elaboration of **FCV procurement plans for public fleets** (Question 53), the **labelling of products** according to their CO_2-footprint (Question 42), the **elaboration of inventories** (Question 50) and the **implementation of an information platform** (Question 45) were evaluated as important, midterm urgent and feasible. The **organisation of symposia** (Question 49) was also evaluated as an important mid-term measure, but very feasible. Labelling was evaluated as more important and more feasible during the second course of the Delphi-study. The meaning of symposia and information platforms slightly increased. Experts commented on the measures as follows:

***Public procurement plans**: „Good possibility to rapidly increase the number of units. Because public administrations regularly have large fleets this will be possible with a less extended infrastructure at an early stage. Great idea but very political…..certainly would provide a market. Suitable vehicles are not available."*

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276 http://www.theicct.org/blogs/staff/eu-vote-cars-co2, 19.09.2013

***Labelling of CO_2-footprint**: "Think this is on its way in Europe but is not as important as some of the policy measures in my mind. For cars: W-t-W or W-t-T? Probably there will be several practical assessment problems, concentration on the most important CO_2-emitters reasonable."*

***Organisation of symposia** etc.: "In my view there is a lot of this going on - what the H_2-world is not doing is going outside to the people who are less convinced, Already happening. International exchange between governments would be necessary. How many coals else should be carried to Newcastle? At the H_2FC Annual Platform meeting they still have an incredible amount of financing, and everyone was complaining that governments aren't funding them enough."*

***Research inventory**: "Think it has been/is already done. Probably already existing; Since 1986 the EU has spent some G€1.02 on H_2FC-development. Unbelievable! The lacking clarity on support programmes is among their complexity one of the main disadvantages of the EU compared to Northern America."*

***Implement information platform**: Not sure of the 'erdgas initiative', but if it has been done for that then it can be easily done for FC-users and is important because it is a breakthrough technology. Sales handbook: no, practical tests: yes; The membership in a special club should not be the target, but it has to be made clear that FCVs are an alternative for the mass market; Only for freaks, word of mouth is more important; A real market for private FCVs not before 2015; According to the design; If FCVs would be freely available."*

All measures were classified as mid-term measures by the experts. Standardisation and training were evaluated as the most important and feasible tasks for promoting market development. These measures could be organised by the stakeholders of H_2-fuel themselves. Also, financial support from the State, e.g. tax exemption for H_2-fuel, grants for the H_2-infrastructure or buying an FCV and support for the production of RES-H_2 were evaluated as important. Some experts requested developing a funding strategy for hydrogen and other sustainable propulsion systems. The positive discrimination of H_2-fuel should be avoided so as not to create a negative image for the fuel. Early information on future EU CO_2-fleet standards is seen as a better driver than a follow-up to the Kyoto agreement. It would force the industry to act, if, at the same time, a lead time allows for the necessary developing of suitable technologies. The measures added for the second Delphi round were generally evaluated as less important which indicates that the original selection of measures was sufficient.

Question	a) Importance	b) Urgency	c) Feasibility
36) Implement standards to define vehicle filling, e.g. adapter, pressure curve, pre-cooling temperature	5 **+7/-0** **+7**	3 **+6/-7** **-1**	5 **+2/-0** **+2**
47) Train existing maintenance and repair personnel to service FCVs	5 **+7/-0** **+7**	3 **+4/-4** **0**	5 **+5/-0** **+5**
46) Include maintenance and repair of fuel cell vehicles as well as safe garage operation and equipment to the education of new service staff	5 **+4/-0** **+4**	3 **+5/-5** **0**	5 **+4/-0** **+3**
37) Reliable mineral oil tax exemption for hydrogen as a fuel for at least 10 years	5 **+4/-0** **+4**	3 **+6/-4** **+2**	4 **+2/-2** **0**
39) Public co-funding of hydrogen infrastructure beyond the first demonstration projects	5 **+5/-0** **+5**	3 **+6/-5** **+1**	4 **+4/-2** **+2**

Question	a) Impor-tance	b) Ur-gency	c) Fea-sibility
43) International mandatory targets for further CO_2-reduction beyond 'Kyoto-agreement' are available and kept by nations	5 +2/-0 +2	3 +9/-5 +4	3 +3/-4 -1
40) Early decision on further tightening of EU car fleet standard from 130 g CO_2/km in 2012 and 95 g CO_2/km in 2020 to e.g. 75 g CO_2/km in 2030	4 +5/-1 +4	3 +8/-7 +1	4 +9/-2 +7
41) Inclusion of transport into the Emission Trading Scheme of the EU	4 +3/-1 +2	3 +7/-3 -4	4 +2/-0 +2
48) Train sales personnel to better market fuel cell vehicles among conventional vehicles	4 +3/-2 +1	3 +1/-3 -2	4 +4/0 +4
52) Financial support for the production of regenerative hydrogen	4	3	4
38) Unbureaucratic direct subsidies for fleet and private fuel cell car purchasers, e.g. k5 €/car	4 +7/-2 +5	3 +4/-5 -1	3 +4/-4 +0
44) Introduce strong CO_2-component to the tax concessions granted for commercially and privately used company cars	4 +1/-2 -1	3 +6/-6 0	4 +6/-3 +3
53) Procurement plan to equip the public fleet of ministries, public organisations etc. with fuel cell vehicles	4	3	4
42) Products and services are regularly labelled according to their CO_2-footprint	4 +7/-2 +5	3 +6/-6 0	4 +11/-1 +10
49) Organise symposia at professional society meetings to stimulate further research and co-operation on fuel cell vehicle technology and infrastructure development	4 +3/-2 +1	3 +4/-3 +1	5 +4/-1 +3
50) Elaboration of an inventory of new information, research underway, and potential funding sources at national and European level	4 +7/-3 +4	3 +3/-7 -4	4 +3/-2 -1
45) Implement information platform for FCV-users and purchasers comparable to German national "Erdgasinitiative"	4 +0/-0 0	3 +2/-4 -2	4 +4/-1 +3
51) Payment of an "H_2-Cent" - charged from each litre of gasoline or diesel sold - to the building-up of a hydrogen infrastructure	3	3	2.5

Figure 6-38: Evaluation of the importance, urgency and feasibility of various measures to promote the market introduction of H_2-fuel[277]

[277] For ranking within the groups the mean has been used.

6.4 Application of the Porter Model of Five Competitive Forces

The successful introduction of new products to the market is – among the customer acceptance of the product itself - mainly influenced by the competitive conditions. These competitive conditions relate a company and its product to its environment. Although the relevant environment is very broad, encompassing social and economic forces, the key aspect of the firm and its products is the industry in which it competes. In the former sections a detailed analysis of the market environment and the industry was carried out. The main lessons learned about driving and inhibiting forces for the market penetration of H_2-fuel were discussed with a group of experts in the Delphi analysis. In the following, the results are structured, summarised and, finally, assessed using the Porter Model of the Five Competing Forces in an adapted version.

The "Five Competitive Forces" is a tool developed by Michael Porter for the evaluation of an industry structure and its underlying mechanisms or forces. It can also be applied to the market introduction of advanced transport technologies. [Carle et.al., 2006, p. 6] Within the model, **industry** shall be defined as a group of firms producing products that are close substitutes for each other. Forces outside the industry are relevant only in a relative sense, because they usually affect all firms and products in the industry. Availability of an H_2-infrastructure and costs of H_2-fuel provision are important external forces which influence all FCV-manufacturers in the same way. The strength of this influence is discussed in section 4 reflecting the specific market characteristics for H_2&FCV-technology because both technologies are indispensably intertwined, today.

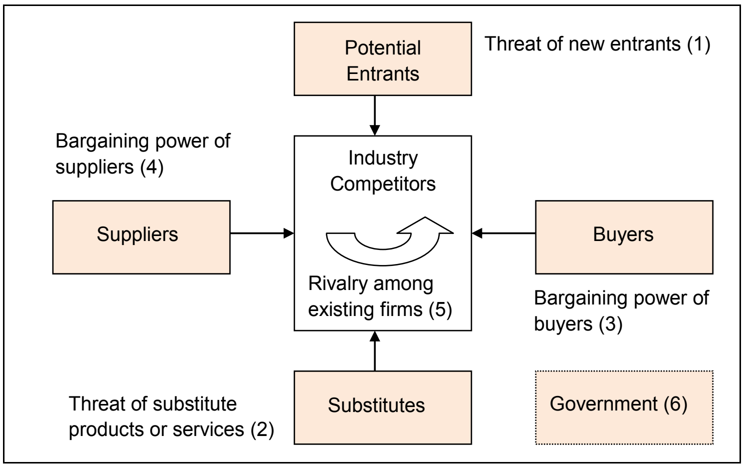


Figure 6-39: Porter's Five Forces of Competition [Porter, 1980, p. 4]

The key is found in the differing abilities of firms/products to deal with the different internal and external forces. Porter identified five fundamental competitive forces, (see *Figure 6-39*). [Porter, 1980, p. 3, 5] Three forces result from 'horizontal' competition on the industry's level, i.e. the threat of substitute products, the threat of established rivals (i.e. other vehicle manufacturers) and the threat of new entrants (e.g. Tesla is a new entrant to the sports car market). Two more forces cause a 'vertical' competition, i.e. the bargaining power of suppliers and the bargaining power of customers. Government is often called the sixth force because it sets the institutional framework conditions. The impact of this force is particularly important because advanced transport technologies often make a positive contribution to air quality, energy security etc., but these contributions have no market price, see section 5.2.

The collective strengths of all forces determine the ultimate profit potential in the industry. Profit potential is measured in terms of long run return of capital invested. It is used as an indicator for the **market potential** of H_2FCV-technology or other new competitors. **Competition** is used in a broader sense of extended rivalry, reflecting the fact that competition in the industry goes well beyond rivalry among current competitors, but including the threat of substitutes, bargaining power of suppliers and buyers. In the classical model, all five forces jointly determine the intensity of the industry competition and profitability.

In the case of H_2FCV-technology all companies are new to the market, but there are some companies which have developed their market entry strategies more intensively than others, e.g. through extended R&D. The inner industry rivals on H_2FCV-technology are defined as those FCV-manufacturers which have recently announced market entry by 2020. The threat from or opportunities for new entrants result from FCV-manufacturers entering the market later, such as Renault and Peugeot, both of whom are currently concentrating on technologies like BEVs. There may be also some Chinese companies preparing for market entry, but available information is rare. However, it is regularly argued that public FCV-funding is needed to combat the threat that Chinese vehicle manufacturers would gain significant market shares using superior FC-technology instead of the ICE, which has been developed to a superior standard by the 'large automobile nation companies'. In July 2014, China has been mandating that electric cars (BEVs, PHEVs, FCVs) make up at least 30% of government vehicle purchases by 2016. China also announced to exempt new-energy vehicles from a 10% purchase tax between 2014 and 2017. The government has identified EVs as a strategic industry to help it gain global leadership, reduce energy dependence and cut smog.[278]

The market power of FC-, other component suppliers and FCV-customers is considered. There will be a high threat from substitute products (i.e. other alternative drive systems and the incumbent ICEs). The strongest forces are crucial to the success of market penetration and also involve the highest threat for market failure. In the case of H_2FCV-technology the Delphi-Analysis identified as strongest of the forces: the threat of substitute products and the framework given by the government. The specific forces and framework conditions are depicted in *Figure 6-40*. However, this underlying structure of the industry should be distinguished from the many short-run factors that can affect competition and profitability in a transient way. The following analysis is carried out under the assumption that H_2FCVs are entering the market by 2050.

6.4.1 Entry to FCV-technology and intensity of rivalry between actors [Porter, 1980, p. 7-17]

Firms active in H_2FCV-technology are mutually dependent. This interdependence overshadows the usual competition between these companies. Conventional mechanisms of defending market shares do not work during the market introduction phase of H_2FCV-technology. This is expressed through the cooperation agreements between individual companies targeted at a cheaper and faster technology development, see section 6.1. The establishment of inter-industry alliances to support the marketing process is an even more important indicator (CEP and H_2-mobility in Germany), because companies agree to subordinate their future activities to contracts and binding commitments. Even public relations work is carried out jointly up to a certain level. In addition, governmental representatives are participating in these alliances providing, on the one hand, subsidies for technology development and, on the other hand, guaranteeing a more or less non-discriminatory access by all stakeholders to these alliances. Nevertheless, in the future, following successful implementation of an FCV-market the same rivalry as in the conventional vehicle market has to be expected.

The exit barriers from H_2FCV-technology are high due to the high R&D efforts already made. In addition, strategic interrelations, emotional barriers and governmental or environmental restrictions are high. Furthermore, a proprietary technology such as H_2FCV-technology usually needs specialised assets resulting in a further raise of entry and exit barriers, increasing the profit potential, but also the related risks. For entry to the early market phase, the industry will

[278] http://www.bloomberg.com/news/2014-07-13/china-targets-30-new-government-vehicles-use-alternative-energy.html; 17.08.2014

need to invest more money on production facilities, production ramp up, H_2-infrastructure, FCV distribution and service infrastructure etc. If the industry were to do so, it would make another stake for the technology, linking financial success and image to H_2FCV-technology. Today, the industry is aware of the efforts yet to come, but is regularly announcing market entry within the next three years. This again increases the exit barriers. The H_2FCV technology stakeholders are mainly multinational groups following more or less identical goals and strategies. This may facilitate the predictability of market development. [Porter, 1980, p. 18-23]

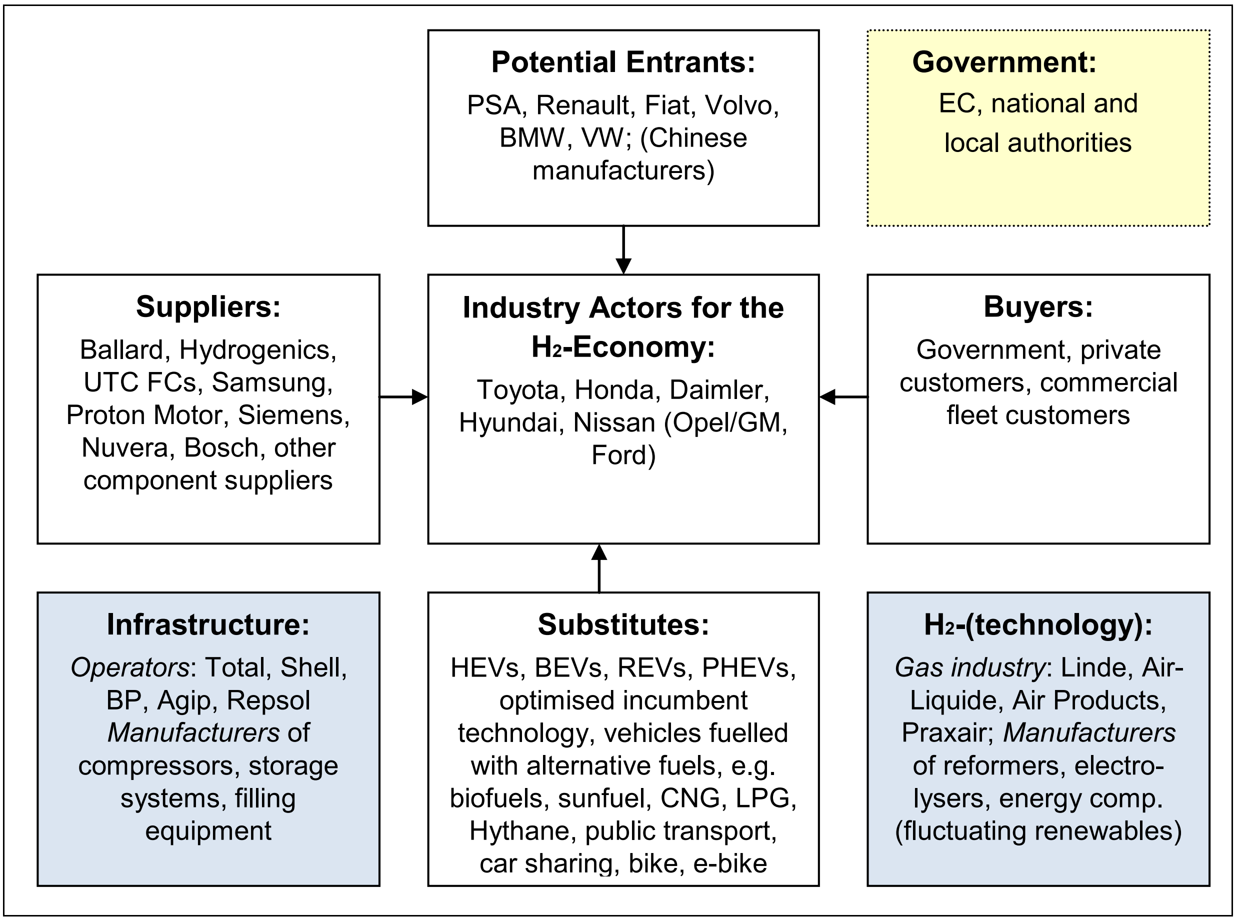


Figure 6-40: Porter's Five Forces adapted to the hydrogen economy

The market barriers to new competitors are high due to the high technical knowledge and high investments necessary for the development of FCVs. However, the close technological link to other alternative vehicles (BEVs, HEVs, PHEV, NGVs) would also allow later access to the technology using externally bought FC and related system know-how.

New entrants to an industry bring new capacity. This could also be an opportunity for H_2-fuel to seize, because it is linked to the availability of more FCV-models, more FCVs on the road, greater attention on H_2FCV-technology, a higher capacity usage of the H_2-infrastructure etc. However, it is also linked to the desire to gain market share and substantial resources. Prices can bid down (which would be good for the development of the H_2-economy, but bad for cost covering by manufacturers) and even 'substitute vehicle' costs may be forced to be reduced as a result. In general, the threat of entry depends on the altitude of market entry barriers. Since all manufacturers are currently facing these barriers, the following is true for the new entrants and stakeholders of H_2-fuel.

Economies of scales are defined as the connection between the unit costs of a product and the absolute volume produced per period: Economies of scales will heavily influence FCV-costs simply through the increase in number of units as well as the gain in learning effects, see section 5.4. In addition, a large FCV market share in leading automotive markets (Germany, California) would restrict the production of other propulsion systems at least in specific segments (e.g. SUVs). Propulsion technologies with a smaller market or selling in the same segment would be hit first, e.g. Porsche and Tesla are direct rivals. FCVs may be able to compete first with large vehicles, which need to reduce costly CO_2-emissions. Also, privately used commercial cars could be an interesting market, because green company policies may restrict the purchase of conventional large and fast vehicles. In these vehicle segments users are less sensitive to price, but more receptive to technology innovation and image. Most technologies, which are standard today, have emerged from the elevated vehicle segment, because users are more ready to pay for a premium technology and the relative price premium is less. Examples include air bag, navigation system etc.

In particular, the number of FCVs on the road influences the market price of hydrogen. The capacity of the H_2-infrastructure would be better used and fixed costs could be distributed to a larger volume. An enlarged H_2-production and distribution system could change from distributed production and truck transport to more efficient central production or even pipeline transport to distribution centres for large H_2-volumes in the long-term. Forecasts show that this would result in significant price reductions, see section 4.2.4.2. In general, all segments of the H_2-production and distribution industry would be stimulated, including R&D. The H_2-fuel price, or rather the price difference to incumbent fuel, has an important impact on FCV's TCOs, again, in particular in the large vehicle segment, which is characterised by a high specific consumption and a high mileage.

Product differentiation means that established companies and technologies have brand identification and customer loyalties. H_2FCV-technology will enter the market mainly through established vehicle manufacturers and mineral oil companies. This is different to BEVs where vehicles are also produced by smaller manufacturers such as German e.cars, e-Wolf, Karabag, Tesla etc. The current stakeholders of H_2FCV technology development are market leaders in today's conventional technology (Toyota, Daimler, Honda, Shell, Total, Linde, AirLiquide etc. to name only a few). Thus, no totally new brand identification and loyalty has to be established. In this work, it is also expected that product differentiation between FCV-manufacturers will be overshadowed by the need of FCV-technology to differentiate against the other propulsion systems in the first instance. **Direct FCV differentiation properties** are described in section 5.2.

Within the framework of this thesis, it is not expected that great customer loyalty to conventional liquid fuels will be found as long as the comfort of filling is comparable to the comfort and service found at the conventional filling station (payment procedure, shop etc.). The H_2-filling nozzle is even cleaner than the conventional one.

The market introduction of H_2FCV-technology will have huge **capital requirements** on *R&D and development of production facilities*: the patent analysis demonstrated that H_2FCV technology R&D effort is quite substantial, see section 6.2. In the case of technology failure, these investments would be stranded. The effort for the implementation of the manufacturing processes, which are rarely patented, is very high and must be added to basic R&D costs. This includes the implementation of line production facilities for mass production of H_2-containers, FCs (MEA), hybrid and control systems etc. and, finally, FCV-assembly, see section 6.4.3. Central H_2-production and distribution already exist at mass production level. Technologies for decentralised production partly need to mature technologically and miss economy of scales, e.g. electrolysers. The H_2-infrastructure introduction plan of H_2-mobility showed that investments in a first German H_2-network are at least 700 M€, see section 4.2.4.2. Companies will invest in manufacturing capacities only if they can rely on the political framework conditions, the current CO_2-fleet standards is codified only to 95 gCO_2/km.

Costs for switching between transport technologies incurred by the customer: after investing in an FCV, the private customer would still face switching costs. During the early market entry phase, he/she has to expect additional efforts to reach a filling station and a specialised service point. FCV service providers will face higher costs for retraining personnel, for new ancillary equipment (tools, safety equipment in the garages to detect and mitigate risks from the use of H_2-fuel and high voltage) and effort for testing and qualifying the new technology. Fleet operators may even need to invest in the construction and operation of their own H_2-filling stations to quickly fill a larger number of FCVs. These fleet operators will face the risk of becoming “locked” if the market introduction fails and the H_2-infrastructure does not develop as assumed. In this case, the resale value of the FCV will collapse totally. Nevertheless, resale will only be possible to markets with an H_2-infrastructure, eliminating popular second-hand car markets in Eastern Europe or Africa.

Experience from the market entry of NGVs has shown that enthusiastic customers may also have to expect difficulties to access distribution channels, i.e. finding a dealer who is able and willing to sell an FCV. The number of models available will in any case be limited during the market entry phase. The industry will need to choose the right marketing strategy to sell the benefits of H_2FCV-technology in wide reaching image campaigns to make the customer willing to substitute. In any case, decreasing prices will be indispensable to market success. In addition, several framework conditions of government policy are still unclear such as process for obtaining infrastructure building permissions, procedures to calculate the CO_2-fleet emission etc.

6.4.2 Pressure from substitute products

The absolute impact of any substitutes, conventional or alternative vehicles, on the market penetration of FCVs depends on the quality and price of the substitutes and the (forced) willingness of the buyer to substitute. The future main competitors for FCVs can be identified from the Delphi Analysis (question 8). **Serious substitute competitors to FCVs will be the fully hybridised and partly biofuelled incumbent propulsion systems (in the following HEVs and PHEVs) and BEVs, i.e. the other variation of the fully electrified car**. According to the Delphi analysis and several other studies, the car will remain the main passenger transport means. This disqualifies public transport and other non-motorised mobility options as serious competitors.

There is also a likelihood of retaliation from existing industry players who will try to defend market shares of conventional vehicles, e.g. in February 2007 the European car industry gathered under the umbrella of ACEA to jointly lobby against the European Commission legislation to meet the long announced, and already postponed, target of 120 gCO_2/km.

FCVs compete in several characteristics with the substitute products. The most relevant characteristics are evaluated in the following on the basis of the results of the former chapters and additional information for HEVs, PHEVs, BEVs and FCVs using a scoring range of five[279] for the time horizons of today, 2030 and 2050. The evaluation is naturally coupled with the uncertainty of future developments. All cost forecasts are based on a collection of assumptions which cannot be verified today, since only the technology pathways for the next five

[279] 1= unsuitable, 2= barely suitable, 3= neutral, 4= suitable, 5=very suitable

years can more or less be tracked. The technology characteristics could be distinguished according to their impact on societal targets or on customer satisfaction:

- Level of suitability for achievement of the EU air quality and climate targets, see section 3;
- Level of suitability for gaining consumer acceptance.

If not mentioned otherwise, the benchmark is the technology with the current best performance applied in a vehicle of the C/D segment, the main target market of FCVs. The evaluation assumes that the legislator will request an intermediate car fleet target of 65 gCO_2/km by 2030. This would be necessary to achieve the EU 2050 transport target of 60% CO_2-reduction **(which would require a car fleet in use complying at least to 25 gCO_2/km[280] by 2050)**. In the following a more conservative fleet target of 40 gCO_2/km is assumed. By 2050, it is expected that all ICE-vehicles would be fully hybridised, thus HEVs will be a ubiquitous technology and ICEs will fall out of the evaluation system.

The vehicle sales price has a high marketing value; the achievement of a good buying price contributes to customer satisfaction, in particular of private buyers. Substitutes for FCV propulsion systems place a ceiling on FCV-prices that could be charged. At current prices FCVs could not be sold widely. For example, the current leasing rate of the B-Cell is more than 700 €/month; the petrol B170 costs 25 k€. The price of the basic Toyota Prius is 27 k€, the PHEV-version adds another 8.65 k€ to this purchase price. According to the US DOE, the PHEV-premium will likely be 1-7 kUSD compared to non-PHEVs.[281]

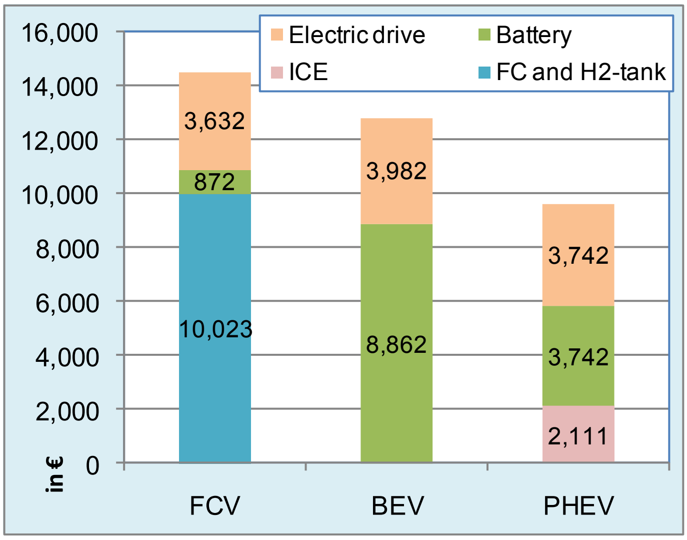


Figure 6-41: Total power train costs, C/D segment by 2020 [McKinsey, 2010, p. 36][282]

Highly energy efficiency improved ICE-technologies would increase the complexity and cost of these vehicles. For a 2020 spark ignition power train the additional costs for a vehicle of the C/D-segment would be about 3.1 k€ according to the McKinsey study. [McKinsey, 2010, p. 36] In 2013 about M3 vehicles were newly registered in Germany with an average emission of 136.4 gCO_2/km. By 2021 a fleet limit of about 100 gCO_2/km will have to be achieved in Germany taking into account the current weight factor. The current fee for failing the fleet limit is 95 €/gCO_2/km. The theoretical annual fee, if the car manufacturers stay with the actual fleet emission, would be 36 gCO_2/km*3M*95 €/gCO_2/km = 10.26 G€/a. This value is the theoretical ceiling for any investment, i.e. additional costs of 3.42 k€/vehicle.

280 In 1997 (the earliest figure available), the average fleet emission was 182 gCO_2/km. The annual growth of car transport performance in pkm was 1.0% between 2000 and 2010 and was estimated to increase to 1.3% between 2010-2030. For the following calculation an annual increase of only 1% is assumed between 1990 and 2050, thus on a percentage base mileage increases to: 100 km * 1.01^60 = 182 km. In 1990 a mileage of 100 km caused 18.2 $kgCO_2$. The equation for the achievement of a 60% reduction of absolute emission is: (182 gCO_2/km * 100 km) * 0.4 = 72.8 $kgCO_2$= (x gCO_2/km * 182 km): **x = 25 gCO_2/km (newly registered cars and cars in use).**

281 http://www.fueleconomy.gov/feg/phevtech.shtml; 04.10.2013

282 All power trains have different performance criteria, mobility patterns and driving purpose, different types of batteries for each power-train depending on their driving pattern (battery capacities: FCV 1.3 kWh; BEV 29.7 kWh, PHEV 12.4 kWh)

Today's battery costs result in a price premium of 15-40 k€ to the BEV. The BEV-manufacturers offer battery leasing concepts to attract customers with a “Carefree Package”, e.g. the Renault Kangoo battery could be rented for 82 €/month.[283] The customer receives the most advanced battery technology and has no risk in the event of an early deterioration of performance. However, this concept is not cost covering; the income during the contract duration would be less than 3 k€, and would only work economically with strongly decreasing battery costs and increased battery durability. In addition, BEVs require cost and effort from the customer to provide a charging point close to its household (connection, contract, organisation etc.). This may become also an emotional factor, if the family’s second car is occupying the garage. In addition, the various charging strategies of the car manufacturers may cause concern to the consumer as to which system to choose today, and which technical solution would still be valid throughout the lifetime of the BEV.

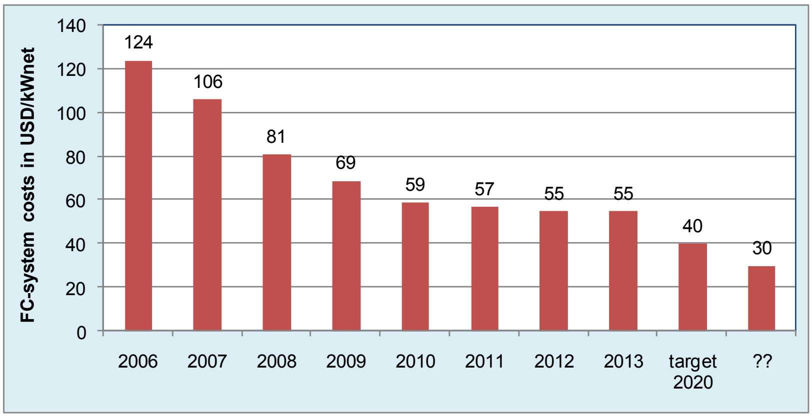


Figure 6-42: Automotive FC cost development[284]

Toyota announced a sales price for its ‘2015 FCV’ of less than 51 k€ for market introduction in Japan; the sales price for the US and the EU has not yet been unveiled. According to forecasts based on manufacturers’ data, the cost of FC-systems is expected to decrease by 90% and component costs for BEVs by 80% by 2020, due to economies of scale and incremental technology improvements. McKinsey forecasted total power train costs for FCVs, BEVs and PHEVs, see *Figure 6-41*. By 2050, the FCV sales prices will still be about 4-5 k€ higher than for the incumbent vehicle according to McKinsey, see *Figure 4-53*.[285] The 2020 DOE FC-system cost target is 40 USD/kW, see *Figure 6-42*.

There may be cost disadvantages for the new H_2FCV-technology independent of scale. Most of the technology components used are still proprietary product technologies that are offered by a limited number of producers. H_2FCV-technology is progressing on the learning curve, i.e. there is a large potential for cost reduction through learning in the overall industry. This desired cost reduction might also be a disadvantage for early adopters, because if costs of new vehicles decline, the resale value of used cars also decreases.

Vehicle sales price[286]	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	very suitable	suitable	neutral	barely suitable	unsuitable
By 2030	very suitable	very suitable	suitable	neutral	neutral
By 2050		very suitable	suitable	suitable	suitable

Fuel price and fuel economy: the petrol B-class 170 consumes 7.7 l/100, equalling about 12 €/100 km fuel costs. The actual consumption of the Toyota Prius is about 4.6 l/100 km;

283 Annual circulation of 10 Tkm, 36 month contract duration, http://www.leasing-elektroauto.info/-leasing/elektroauto-batterie-leasing/; 10.02.2014

284 http://energy.gov/eere/fuelcells/accomplishments-and-progress; 29.08.2014

285 Calculations are based on a mass production (M1 FCVs, M3 BEVs in the EU by 2020, with infrastructure a key prerequisite to be in place. [McKinsey 2010, p. 3]

286 Deviation of less than 10% (very suitable), 20%, 30%, 50%; >70% (unsuitable) from the best value, see also *Figure 4-53*.

which is only equivalent to 7.60 €/km. [ADAC] Assuming an equal consumption on petrol, the Prius PHEV needs more than 0.3 Mkm on electricity to amortise in comparison to the standard Prius.[287] Future energy price development in the light of further expansion of renewable energies and with regard to the current conflicts in the Arabic regions and in Eastern Ukraine are difficult to predict.

The B-Cell consumes about 1.0 kgH_2/100 km, which currently equals 9.50 €/km. However, electricity and hydrogen are not taxed at present. This untaxed H_2-fuel could compete with fossil fuels even today. H_2-fuel costs are expected to decrease by 70% by 2025 due to a higher utilisation of the H_2-infrastructure (max. utilisation of 80% should already be reached by 2020) and economies of scale in production. The EC is targeting a price of 5 €/kg$H_2$by 2015; a price of 2-4 USD/kgH_2 (produced and dispensed) is targeted by DOE depending on the production pathway by 2020. This would equal a price of 0.54-1.09 USD/l_{petrol} (0.42-0.84 €/l) compared to the energy content (w/o taxes) and would allow driving for around 2-3 €/100 km fuel costs (w/o taxes). The H_2-fuel price reflects the infrastructure costs indirectly.

The following evaluation of the competitiveness of the fuel price is based on the assumption that the tax benefit for electricity and hydrogen is reduced only in parallel to decreasing H_2-production costs, i.e. battery costs for BEVs. In addition, it is assumed that the level of future fuel taxes will strongly depend on the fuel's CO_2-footprint. The fossil fuel sales price is expected to rise, see section 6.4.3.

Fuel costs[288]	**ICE**	**HEV**	**PHEV**[289]	**BEV**	**FCV**
Today	barely suitable	suitable	very suitable	very suitable	neutral
By 2030	unsuitable	neutral	suitable	very suitable	very suitable
By 2050		neutral	suitable	very suitable	very suitable

However, a cost comparison of different vehicle concepts has to be based on **Total Costs of Ownership (TCOs)**. TCOs are the main decision factor in particular for commercial consumers buying new cars. The majority of new cars are registered by commercial owners. Commercial cars which are also used privately feature naturally in both camps. The individual company's reimbursement arrangements and how these vehicles are being used (i.e. for what purpose) are decisive for the primacy of vehicle purchase price, TCOs or other factors in decision making. In particular for commercial vehicles with private use charging at home will raise questions of reimbursement costs for electricity, for the installation of a wall box or for the enforcement of the customer connected load and the handling of any tax benefit.

TCO-calculations need to consider (regional) differences in average mileage, fuel cost, CO_2-regulation as well as taxes. The ICE currently has the lowest TCOs. BEVs and FCVs have a higher purchase price than ICEs (battery and FC-related) and lower fuel costs (due to greater efficiency and tax benefits due to lower CO_2-footprint and subsidies). Maintenance costs could not yet be verified, but should be lower due to fewer rotating parts. In addition, the substitution of fossil fuels reduces the mid-term price risk.

Figure 6-43 depicts future TCOs of different power trains according to McKinsey. By 2020, PHEVs will be more economical than BEVs and FCVs. McKinsey predicts that the TCOs of all power-trains will converge after 2025 or sooner with tax exemptions or incentives during the ramp-up phase. By 2030 BEVs shall be cost-competitive with PHEVs for smaller cars.

[287] 16 kWh/100 km*27 ct/kWh (household, green electricity) = 4.32 €/100 km; 4.6 l/100 km*1,50 €/l= 6.90 €/100 km; Δ=2.58 €/100 km

[288] Deviation of less than 50%, 100%, 150%, 200%, 250% from the best value, see also *Figure 4-53*.

[289] In the following it is assumed that PHEVs are usually driving electrically, because most trips are short.

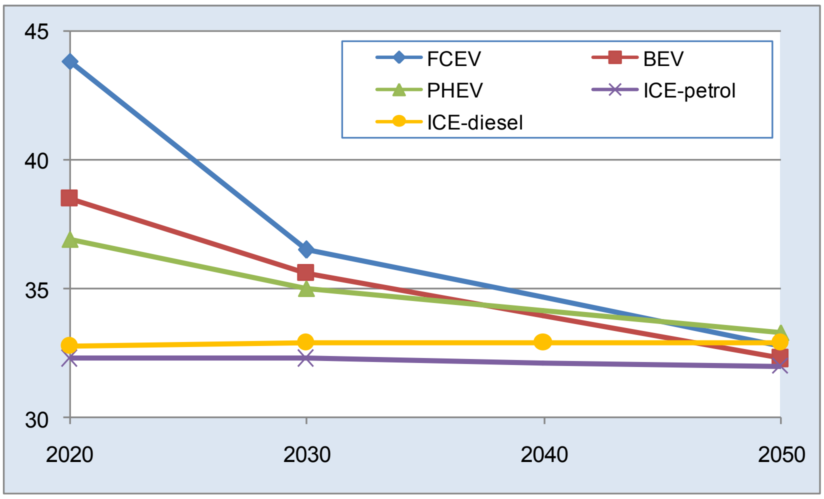


Figure 6-43: TCOs of different power-train technologies in the CD-segment [McKinsey,2010, p. 39]

PHEVs and BEVs will be less competitive than FCVs for larger cars. The costs of ICEs will also increase due to full hybridisation. By 2050, FCV's TCO is expected to be lower than that of the ICE in the largest car segments, too. For medium-sized cars, the TCOs for all technologies should have converged by 2050. BEVs shall have a (small) TCO advantage over FCVs in the smaller car segment. [McKinsey, 2010, p. 5-6]

BCG analysed the TCOs[290] of various propulsion systems in Germany, see *Figure 6-44*. By 2020, the CO_2-reduction costs are expected to reach 140-280 USD for electrification and 70-140 USD for advanced ICE technology per percentage point. Without any subsidies for PHEVs/BEVs and moderate oil prices advanced diesel systems will remain the most cost effective alternative. (Only if battery costs drop below 500 USD/kWh and oil prices increase to 100-120 USD/bbl will electric vehicles become attractive.)

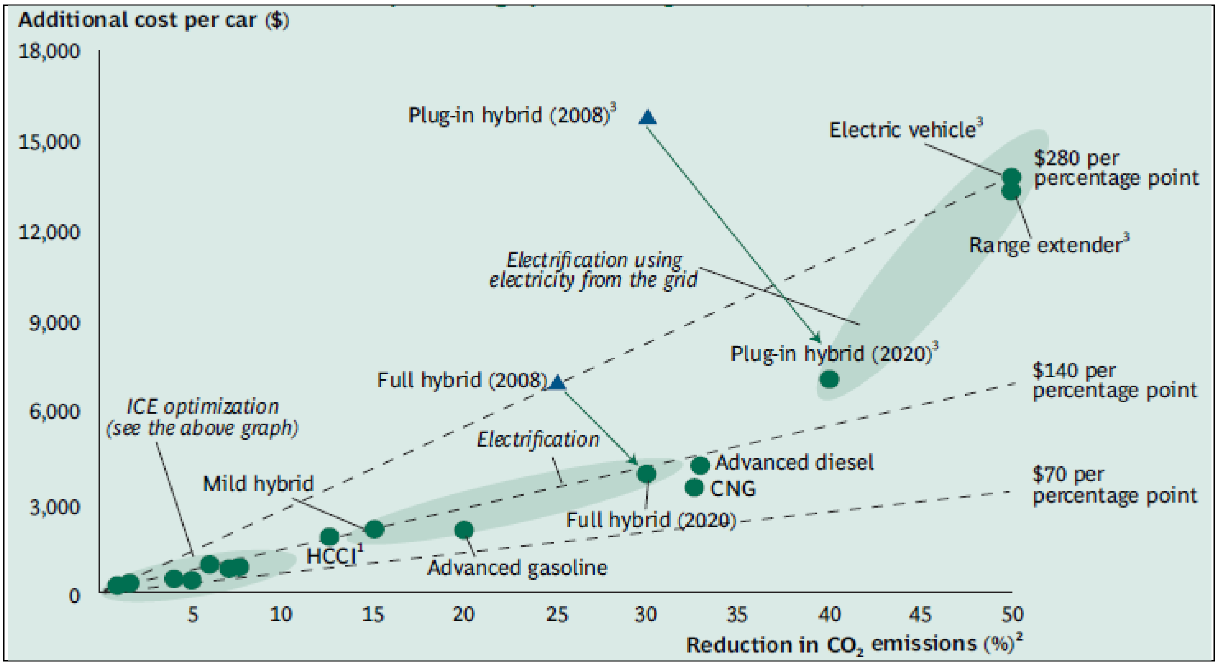


Figure 6-44: BGC forecast of additional costs of alternative propulsion systems by 2020 [Book et.al., 2009, p. 4]

Assuming average learning rates cost competition at TCO level with BEVs and HEVs (later) may be possible by 2030, depending also on the hydrogen costs and the regulatory framework conditions, in particular, the level of external cost internalised, e.g. through a CO_2-related fuel tax. Synergies from energy storage infrastructure could heavily influence the

290 The TCOs of cars with an annual mileage of 14.5 k-km for the first five years of usage were compared (no change in the current taxation), including: vehicle depreciation, fuel costs, battery costs, VAT and CO_2-costs, but no insurance or maintenance costs.

hydrogen production costs and reduce distribution efforts; a technology breakthrough of FC stationary technology could also push the learning rates of PEMFCs.

TCOs medium-sized car[291]	ICE	HEV	PHEV	BEV	FCV
Today	very suitable	suitable	neutral	neutral	unsuitable
By 2030	suitable	very suitable	suitable	suitable	neutral
By 2050		very suitable	very suitable	very suitable	very suitable

Quality of a substitute: the central question regarding the quality of any propulsion system is which system can best fulfil the function of the individual car under the valid legal requirements? The first function of a car is the provision of mobility, i.e. ***range, appropriate size and comfort***. According to the results of the Delphi-analysis, FCs are very well suited to application in LDVs, incl. cars (see section 6.4.1).

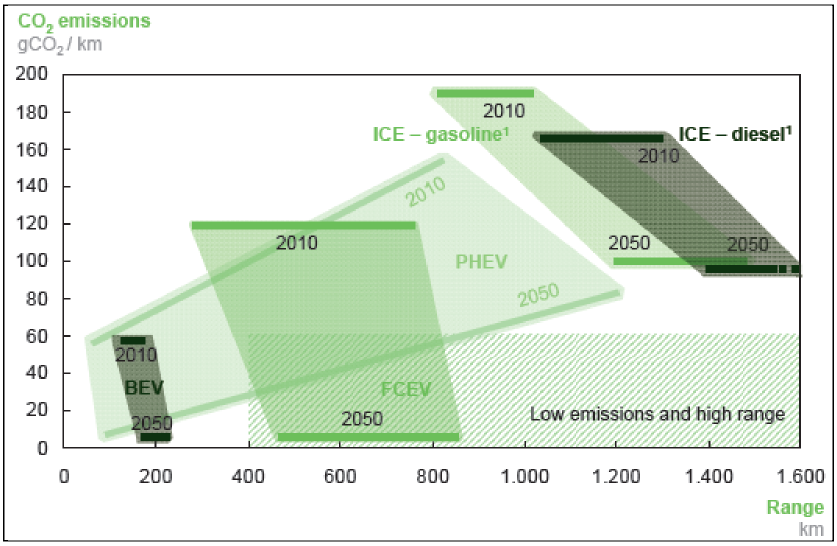


Figure 6-45: Range and CO2-emissions of various propulsion systems 2010 and 2050 [McKinsey, 2010, p. 31]

Hybrid technologies, with an improved energy efficiency, provide the best ***range&refuelling time*** with the current tank sizes, see *Figure 6-45*. Mileages of up to 1.5 k-km will be possible with one tank-full by 2050. [McKinsey 2010, p. 36; Edwards et.al., 2011 (1), p. 5-7] Furthermore, due to the high density and low pressure storing of fossil fuels, the installation of a larger tank is quite easy (packaging) and cheap. Some manufacturers are offering larger fuel tanks as an additional extra. The increase of the H_2-tank will be difficult due to weight and packaging problems. However, with growing efficiency of the FC drive train, the range will increase.

BEVs are limited through range and vehicle size (to lighter vehicles) due to energy storage restrictions. An average, medium-sized BEV with maximum battery loading cannot drive far beyond 150 km at 120 km/h on the highway (taking expected improvements until 2020 into account). Also, in urban traffic, the driving range of BEVs is limited to around 200 km. The amount of energy available also restricts the use of air conditioning, heating systems and other electrical consumers, in particular during winter times. The BEV top speed is usually regulated downward to keep it within an acceptable range. It is not possible to seriously estimate the future energy density of batteries by 2050. Theoretically, the BEV range could be increased by using more battery cells providing more capacity; however, batteries are still costly and heavy. Tesla represents an exceptional case: the model S has a range of about 390 km (60 kWh battery); the price is 65.3 k€.

Current charging times depend heavily on the technology used. At private homes the charging performance is limited to 22 kW at 400 V AC. Type 2 charging at normal household sockets at 3.3 kW, 230 VAC needs 6-8 h. [Mennekes, 2014, p. 161] At subzero temperatures, the BEV could be connected to an electricity source to keep the battery at a constant

291 Deviation of less than 5%, 10%, 20%, 30%, 40% from the best value

temperature level of approximately 5°C, to increase capacity and to accelerate charging, but at the cost of consuming extra energy. PHEVs have a similar range and performance to ICEs, but electric driving only applies to shorter distances (see BEVs). Model choice will be restricted to larger cars due to the additional weight and costs of the second drive.

FCVs have a good range (around 600 km, up to 800 km with technology developing) and similar refuelling time (< 5 minutes) compared with ICEs. FCVs and BEVs are comparatively heavy without the application of lightweight material.

Range & refuelling time	ICE	HEV	PHEV	BEV	FCV
Today	suitable	very suitable	suitable	barely suitable	neutral
By 2030	suitable	very suitable	suitable	neutral	suitable
By 2050		very suitable	open	open	suitable

Access to public infrastructure: the density of the rural station network for conventional fuels is the benchmark for all other propulsion systems (in urban areas only a sufficient network is necessary), see section 2.4. Today, BEVs and FCVs lack a public infrastructure, but concepts for area-covering station networks already exist. The degree of organisation and maturity of the development of a German public H_2-station network is higher than for charging points. Public H_2-stations are integrated within the existing filling station network. Thus, filling would be convenient for users in terms of service, shop, billing, use and settlement of fuelling cards. Concrete plans are available for an area-covering station network in Germany, see section 4.1.3.

However, the **availability of a suitable H_2-infrastructure** remains a critical element. This is a precondition for any FCV-sales. The level of market penetration with GCH_2 filling stations depends on the readiness of the mineral oil/energy industry to invest in H_2-distribution and retail facilities and the availability of suppliers to deliver cost efficient and reliable equipment and fuel. Voluntarily, the energy industry will construct this network only in the case of a foreseeable return of investment. Infrastructure providers bear a first-mover risk, making an upfront outlay to build a filling station network that will not be fully utilised for some years. However, the unit cost reduces over time simply because the fixed capital expenditure is used by an increasing number of FCVs and is distributed to a larger H_2-volume. The dynamics of setting up an H_2-filling infrastructure are such that there is a limited opportunity to gain "early mover" advantage, so the first players will not be able to compensate for any losses. Indeed, they will develop the market for all other infrastructure providers who will then reap the benefits at a later stage. [McKinsey, 2010, p. 7-9]

In the first decade of the McKinsey roll-out scenario[292], supply infrastructure costs per car, especially those for a retail infrastructure, are initially higher, due to lower utilisation, see *Figure 6-46*. Nevertheless, sufficient network coverage must be available for consumers. After 10 years this would result in a cumulative economic gap of approximately 25 G€ (about 22 G€ for additional FCV-costs plus 2 G€ for H_2-production and distribution plus 1 G€ for the retail infrastructure). These H_2-stations would be concentrated in high-density areas (large cities, highways), building on existing infrastructure. Building a full European infrastructure for a 25% market share of FCVs would require another 2-3 G€/a after the first decade. While the initial investment is relatively low during the first decade, the risk is high. With the market established, subsequent investment during the second decade will be higher, but present a significantly reduced risk. At the end of the second decade of market introduction any

292 McKinsey assumed a roll-out scenario applying M0.1 FCVs after five years, M1 FCVs after ten years and a 25% share of FCVs of the total EU passenger car market in 2055.

potentially remaining economic gap is expected to be directly passed on to the consumer. Within 40 years about 100 G€ would need to be invested in Europe, see Figure 6-46. The specific costs of 1-2 k€ per vehicle for rolling out an H_2-infrastructure compares to rolling out a charging infrastructure for BEVs. [McKinsey, 2010, p. 7-9] For comparison, the cost of the new Berlin airport has been estimated at 5.4 G€[293].

In reality H_2-infrastructure roll out will only work through government action (see California and EU-model), e.g. through dedicated legislation and funding. For Germany, initial investments to introduce another 50 H_2-dispensers are estimated at 40 M€ (to add one H_2-dispenser to a filling station costs about 700 k€, a large filling station with an electrolyser about 1.5 M€). [Schwarzer, 2012] The NIP has already agreed to co-finance a large share of this investment, see section 4.2.4. The emerging FCV-market requires close synchronisation between infrastructure and vehicle number development in the first decade. This could be administrated by "H_2-mobility" in Germany. Also for cost minimisation, the industries' market launch plan must go hand-in-hand with appropriate government policies. However, it is not certain whether the currently displayed consensus between the car manufacturers, the energy industry and other stakeholders, see section 5.3, would withstand the economic hardships of the introduction of the new technology.

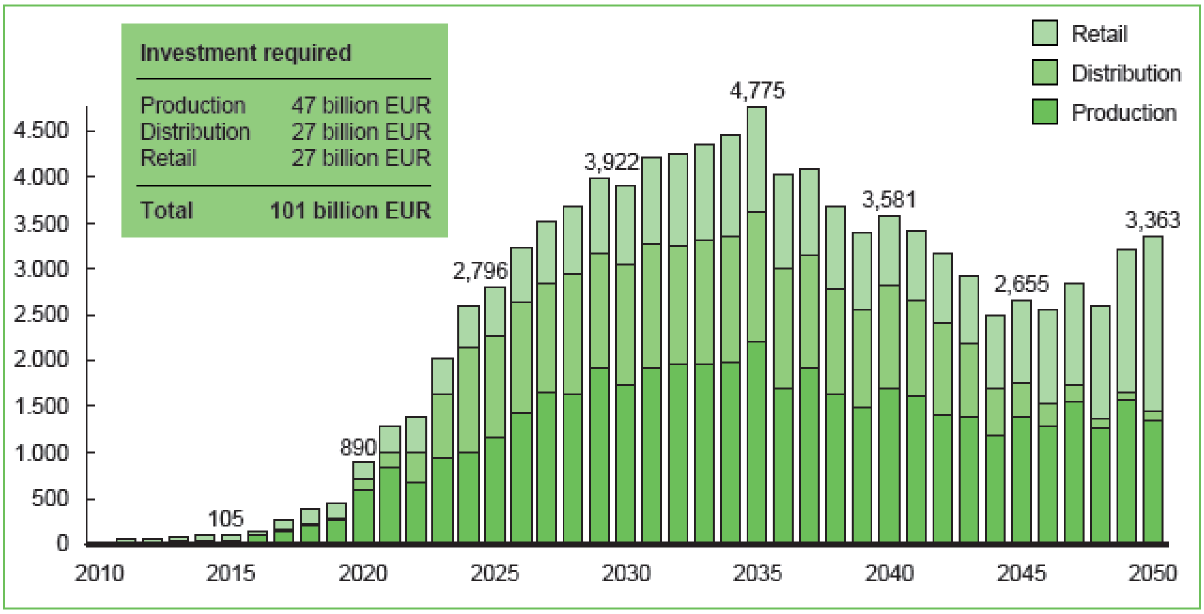


Figure 6-46: Total capital investment for a large-scale roll-out of H_2-supply infrastructure in Europe in M€ over 40 years [McKinsey, 2010, p. 7-9]

Public charging stations may offer type 3 charging with a charging capacity of up to 43 kW. This would reduce charging time significantly. However, these stations suffer under large investment costs and lack a sustainable business concept. The standardisation of DC-charging has not yet been finalised. [Mennekes, 2014, p. 161] The level of extension of the public charging network by 2050 is unclear: neither technology decision (e.g. AC, DC) nor operator and business model questions have yet been clarified. The achievable profit depends heavily on range, fuelling time and home fuelling opportunities.

In Europe, more than 80% of car journeys average below 20 km and Europeans drive less than 40 km per day. This means that most trips could be accommodated by BEVs and FCVs

[293] http://www.spiegel.de/wirtschaft/soziales/mehdorn-berliner-flughafen-ber-soll-1-1-milliarden-euro-mehr-kosten-a-963788.html#spRedirectedFrom=www&referrrer=https://www.google.de/; 20.09.2014

without any problems.[294] The organisational effort for longer, occasional trips would be high for users of FCVs and, in particular, of BEVs.

Access to public infrastructure	**ICE**	**HEV**	**PHEV (electricity)**	**BEV**	**FCV**
Today	very suitable	very suitable	unsuitable	unsuitable	unsuitable
By 2030	very suitable	very suitable	neutral	neutral	neutral
By 2050		very suitable	open	open	suitable

Since 2007, the EU car fleet (mainly ICEs) has reduced its ***CO_2-footprint*** by 18%; the total reduction by 2021 shall be 40% (mixed fleet). According to the McKinsey study, middle-sized diesel and petrol fuelled vehicles will be limited to around 100 gCO_2/km after 2020. Even if future technology developments and learning effects cannot yet be quantified in detail, these reductions will not be large enough to comply with the 60% transport-related CO_2-reduction target of the EU by 2050 (*see footnote 280*). A current estimation of the ICE's efficiency potential - mainly generated through downsizing - is about 20% for spark ignition and 15-20% for compression ignition engines. [Pischinger, 2013] This confirms that the conventional ICE will not be able to achieve CO_2-targets well below 95 gCO_2/km for the period after 2021. Among the power train efficiency the fuel production pathway is a key to GHG-emissions and energy use, (see WtW-analysis in *Figure 6-47*).

WtW	Energy MJ / 100 km	GHG g CO_{2eq} / km
Conventional petrol		
Port Injection Spark Ignition 2010 / hybrid[295]	223 / 190	167 / 143
Direct Injection Spark Ignition 2010 / hybrid 1.3 l	221 / 181	166 / 136
Conventional diesel: DICI 2010 DPF / hybrid 1.6 l	198 / 159	149 / 120
C-H_2, Natural gas 7.000 km, Reforming[296]		
Port Injection Spark Ignition 2010 / hybrid	353 / 313	207 / 183
FCV / hybrid	198 / 176	116 / 103
C-H_2: Electricity EU-mix, Electrolysis		
Port Injection Spark Ignition2010 / hybrid	774 / 686	349 / 310
FCV / hybrid	434 / 387	196 / 174
C-H_2: Wind, Central Electrolysis, Pipe		
Port Injection Spark Ignition 2010 / hybrid	299 / 265	16 / 14
FCV / hybrid	168 / 150	9 / 8

Figure 6-47: WtW energy consumption and CO_2-emissions of various power trains [Edwards et.al., 2011 (1, 2), p. 22, 40]

Petrol, diesel and their blends with a number of alternative liquid fuels could be used in the existing infrastructure and vehicles. The use of "tailor-made-(bio)fuels" is discussed, also to further reduce NO_x- and particulate emission from diesel engines. Nevertheless, these fuels would also need a separate fuel pump and tanks, that have to be available and their GHG-savings critically depend on (biomass) source, manufacturing processes and the fate of by-products. The GHG-balance of some alternative liquid fuels is particularly uncertain because of nitrous oxide emissions from agriculture and the impact of land use change. [Edwards et.al.,

[294] http://www.eea.europa.eu/articles/the-electric-car-2014-a-green-transport-revolution-in-the-making; 26.09.2013

[295] Capacity to run 20 km as ZEV on the battery

[296] Gas Steam Reforming

2011, p. 5-7] Furthermore, the sustainability of the use of these fuels needs to be considered and political support could be tied to stricter sustainability criteria in the future.

The 2021 CO_2-fleet limit value could be still achieved through a combination of manifold power and non-power train measures without the widespread use of BEVs and FCVs. Highly energy efficiency improved petrol, CNG and diesel engine technology could provide a share to achieve the target. However, after 2020, further ICE efficiency improvements are limited and relatively costly, whilst the available amount of biofuels may be limited. The fleet limit will lead to a higher degree of hybridisation of the fleet. OEMs estimate that 80% of vehicles in the C/D-segment will be hybridised by 2020. HEVs and PHEVs are still relying on conventional fuels and the CO_2-reduction potential of full hybridisation is limited to about 10-30%, respectively 40% in the case of PHEVs (see *Figure 6-44* and *Figure 6-47*).

PHEVs are a solution for reducing CO_2-emissions considerably on short trips. However, it is still unclear how this reduction potential will ultimately be translated into legislation to measure CO_2-emissions. BEVs may be fully operated on renewable electricity, but there the problem remains of attributing CO_2-savings of ‘green’ electricity to concrete users. BEVs and FCVs have zero tailpipe emissions, but air pollutant and CO_2-emissions depend heavily on the electricity/hydrogen production pathways.

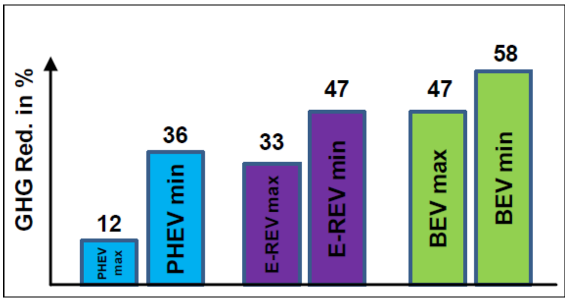


Figure 6-48: EV WtW GHG reduction [Edwards et.al., 2011 (3), p. 27]

The recent (2011) EUCAR, CONCAWE and JRC WtW-analysis shows that BEVs are more energy-efficient over a wide range of primary energy sources and have good results for GHG-emission compared to the reference ICE-vehicle (120 gCO_{2eq}/km TtW or 143 gCO_{2eq}/ km WtW), see *Figure 6-48*. All *EV*-concepts showed GHG-emission savings of 30-60% with an EU electricity mix of 467 gCO_{2eq}/kWh, with only the worst PHEV having a lower potential of about 12%[297]. The 2013 CO_2-footprint of German electricity was 559 gCO_2/kWh (576 gCO_2/kWh in 2012). However, BEVs will only have a significant climate impact if they replace a large amount of the mileage driven in conventional cars; this is contrary to the favoured application in urban transport with a low daily mileage. [Edwards et.al., 2011 (3), p. 27, Icha 2014, p.1] Only FCVs and BEVs using ‘green fuel’ production pathways have the potential to achieve CO_2-emissions of less than 40 gCO_2/km.

The Delphi expert panel favoured H_2-production from wind energy combined with central electrolysis. This would result in WtW-GHG-emissions for an FCV of only 8 gCO_{2eq}/km, see *Figure 6-47*. In addition, it could reduce the heavy dependence of the transport sector on imported oil. FCVs are a feasible low-carbon substitute for ICEs for medium/larger cars and longer trips. Medium/larger cars with above-average driving distance currently account for 50% of all cars and 75% of CO_2-emissions. The CO_2-abatement cost is expected to range between 150 and 200 €/Mg in 2030 and becomes negative for larger FCVs after 2030. [McKinsey, 2010, p. 5-9]

Another major advantage of BEVs and FCVs is their high **energy efficiency**. With a TtW-efficiency in the range of 60 to 80%, BEVs outperform conventional cars up to four-fold. [Edwards et.al., 2011 (3), p. 27] For comparison, the Tesla S consumes 65.2 MJ/100 km. [ECE, R101, http://www.teslamotors.com/de_DE/models, 08.12.2014] Also, FC drive trains show increa-

297 $PHEV_{max/min}$ refers to maximum respectively minimum CO_2-emissions in the fuel pathway (WtT).

sed efficiencies, Scania and Citaro bus projects reported efficiencies of 52-58%, cars achieved 60-63% on the NEDC (see section 4.2.4.5, Annex 8.3). The FC B-Cell has an energy demand of about 120 MJ/100 km (1 kgH_2/100 km); future values will be less according to learning progress. Also, the German energy efficiency target (-50%) could only be fulfilled using BEVs and FCVs by 2050.

Energy efficiency targets, *Figure 4-14*	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	very suitable	very suitable	very suitable	very suitable	very suitable
By 2030	neutral	suitable	suitable	very suitable	very suitable
By 2050		neutral	open	very suitable	very suitable

EU CO_2-targets	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	very suitable	very suitable	very suitable	very suitable	very suitable
By 2030	barely suitable	suitable	suitable	very suitable	very suitable
By 2050		barely suitable	open	very suitable	very suitable

Safety requirements, ***air pollutant emissions***, ***use of hazardous materials*** **and** ***recycling quotas*** are regulated by law and have to be fulfilled independent of the technology used by the various propulsion systems. It is assumed that all vehicle propulsion systems will comply at any time to all safety, recycling and hazardous material requirements.

Currently all propulsion systems are able to comply with the Euro 6 standards, but, in particular for diesel cars, a price increase is expected. Experts from Faurecia, a leading manufacturer of exhaust gas systems, estimates that the contribution of the diesel exhaust gas system to the total vehicle costs will increase from its current 10% to 15% due to technical measures to comply with Euro 6 (this will increase the costs of the exhaust cleaning system by 50-60%). The current premium requested for Euro 6 models in comparison to Euro 5 models is in the range of 1-2 k€.[298]

However, even after the introduction of the very strict Euro 6 standards, compliance with ambient air pollution standards is still a topic in urban areas, in particular for certain air pollutants originating from transport such as NO_x and particulates, see section 3.1. Currently, there are only vague legislative considerations on 'Super Low Emission Vehicles' for achieving the EU’s ambitious clean air targets also in urban areas. Euro 6 standards have just been phased in and technical solutions to further reduce the NO_x and particulate emissions would be very complex and would contradict other targets such as increasing fuel efficiency. The locally zero emission electric drives will be able to comply with any tightened legislation.

Contribution to air pollution reduction	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	suitable	suitable	very suitable	very suitable	very suitable
By 2030	open	open	suitable	very suitable	very suitable
By 2050		open	open	very suitable	very suitable

All alternative vehicle concepts will be available only within a small model diversity during the market entry phase. The incumbent technology offers a wide range of vehicle sizes and additional features. Vehicle noise is difficult to evaluate as it depends heavily on vehicle speed, tyres used and road conditions. Current regulation concentrates on tyres and is

298 http://www.vdi-nachrichten.com/Technik-Wirtschaft/Viel-Stunk-um-neue-Abgasnorm-Euro-6; http://www.welt.de/motor/news/article123963211/Saubere-Dieselmotoren.html, 30.08.2014

therefore independent of the drive train used. However, the noise level in the passenger compartment is an important comfort issue. In general, the electrical drive causes less noise. In an FCV the noise of the compressor has to be added.

Vehicle purchase decisions are also guided by vehicle sizes, brand and design, see *Figure 5-13*. FCVs will be initially introduced in the larger vehicle segment (due to the need for H_2-storage space) providing good comfort. PHEVs and FCVs provide the owner with the image of being an innovator. An image decline of the incumbent technology cannot be ruled out in the future. BEVs, PHEVs and FCVs offer the comfort of electric drives, i.e. immediate acceleration and low noise. As FCVs are not yet on the market, comfort criteria are estimated on the basis of demonstration vehicles. Because of the large level of uncertainty, it has been withdrawn from an evaluation of the comfort criteria for 2050.

Comfort (choice, size, electric drive, image, noise)[299]	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	neutral	suitable	suitable	neutral	suitable
By 2030	barely suitable	suitable	very suitable	neutral	very suitable
By 2050		open	open	open	open

BEVs and FCVs still face serious technology development, durability and reliability constraints. Even if several BEV models are already on the market, future battery chemistry and layout have not yet been decided. Manifold charging options are available on the market. Manufacturers and customers may now follow technological development lines which may prove tempting within five to ten years. It is assumed that BEV- and FCV-technology will further improve with technical progress. These new technologies may benefit from **synergies from the development of other substitute technologies**: H_2FCV will profit from R&D effort and market development of other alternative propulsion systems. Hybrid and electric vehicles are perfecting many of the FC(H)V-components such as electric motor / generator, power control electronics, **peak power energy storage systems** and regenerative braking systems. [Engel, 1997, p. 8; McKinsey, 2010, p. 36] The availability of electrical components, e.g. converters and transformer with the right technical characteristics (e.g. voltage range) and suitability for mobile applications also need to be improved. In addition, any developments which strengthen the gas storage industry, e.g. CNG-containers, would be beneficial to the FCV-industry. FC-producers benefit from the development of stationary and small FC markets, too.

Reliability & durability	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	very suitable	suitable	suitable	barely suitable	barely suitable
By 2030	very suitable	very suitable	very suitable	suitable	suitable
By 2050		open	open	open	open

6.4.3 Suppliers, buyers and the role of government

According to Porter, the suppliers, buyers and the government also constitute market forces. In the following, the supply force is discussed using more general aspects of supply, i.e. development of manufacturing capacities and the availability of resources, including skilled labour and hydrogen supply.

[299] Very suitable: all 5 sub-criteria / suitable: 4 of 5 / neutral: 3 of 5 / barely suitable: 2 of 5

Today, there are no suppliers of serial produced FCs or FCVs. The FCV- and component industry is still under development. In general, the automotive industry is strongly interlinked with the component industry; many car manufacturers own shares of their suppliers, see section 6.2.1. Both industries are highly concentrated, able to produce the same component in high numbers to exactly the same standard. The car industry is a very important (often the only) customer to the component industry, thus its fortune is closely tied to the car industry (and vice versa). Therefore, the component industry has a vested interest in supporting its client through assisting activities such R&D, marketing and lobbying. The components are often not differentiated and the same components could be installed in many different car models or even brands. Common-part-strategies, modular production systems and alliances between car manufacturers are supporting this standardisation process in the industry with the target of gaining cost advantages through scale effects (e.g. through group purchasing). Some suppliers may be in a position to exert bargaining power by threatening to increase prices (or to reduce quality or services), because they are powerful enough. **Bargaining power** depends heavily on the product and the surrounding market, e.g. for highly standardised products differentiation for suppliers is more difficult. Daimler R&D CEO Thomas Weber has evaluated the high standardisation of FC-technology, in particular 70-MPa-technology, as one advantage compared to the ‘electro-mobility technologies’. In his view, only a few standards exist for electro-mobility technologies. [Meiners, 2012, p. 16]

The components necessary for the BoP (humidifiers, cooling system etc.) are established technologies with a high level of standardisation. Also, the electric drive and H_2-tanks are highly standardised. The onboard H_2-system could be purchased at respective companies. Toyota and Hyundai are using H_2-storage tanks which are developed in-house. Electronics, electric motors and system integration suppliers with good competence and a Tier 1 status to facilitate the achievement of large scales are available on the market, e.g. Bosch recently developed an FC energy control system. However, some manufacturers of the new technologies, i.e. H_2-containers, will still have to learn how to act as a Tier 1 or Tier 2 supplier to the automotive industry. The ability of the (future) Tier 1 to supply products of a high and constant quality in large volumes as well as to deliver and provide service globally plays an important role for the car industry; this strengthens the position of these manufacturers.

FC stack manufacturing still has to be implemented and optimised in terms of yield and cost and reducing scrap rate (targeted to less than 5%).[300] The technical and cost core element of the FC-stack is the MEA. MEA-R&D effort is large and chemical knowledge necessary is very different from the core capacities of the car industry, complicating backward integration. Today, the main PEM material is PFSA. There are several global players for PEM and/or MEA production and research, e.g. DuPont (Nafion), Johnson Matthey, PermaPure, but also German medium-sized companies such as 3M Deutschland GmbH or BWT-Fumatech. The VDMA has just published a German component suppliers guide. [VDMA, 2014] MEA-producers have proprietary knowledge, but are not concentrated enough to exert strong bargaining power. The Japanese car manufacturers may benefit from the local industrial infrastructure with many large multi-product companies such as Toshiba and Panasonic which are also involved in PEMFC-technology.[301] Local production could also be preferred, e.g. Toyota’s hybrid technology was solely locally produced (M0.63 in 2011), because it prevents a know-how drain.

[300] Target of the “Fuel Cells and Hydrogen Joint Undertaking” call 2014
[301] http://www.ieafuelcell.com/links.php#id7; 31.08.2014

There is a need for production lines, not only for components, but also for the whole vehicle. Production lines need to be designed scalable to be flexible with increasing production numbers. The example of Toyota shows that it is possible to start with very small production figures, e.g. a few dozen per month. The initial implementation of FCV-production with low unit numbers may be supported through co-operation along the value chain. The expansion of production capacity and the increase in the degree of automation will happen in accordance with market success. Thus, the economic loss would be calculable and manageable, if FCV technology market penetration fails. For cost reasons, FCV-production will be centralised at individual manufacturers or will be realised jointly between manufacturers within the framework of a co-operation. This will need further standardising of the interfaces between components, e.g. voltage levels, to increase unit numbers. During the market introduction phase the vehicle will be mounted to existing and / or adapted platforms, but procedures will be optimised for all drive trains still successfully on the market by 2030.

Today, 30% of the added value of a vehicle comes from the chemical and electronics industry. For BEVs, this share is about 80%. [Heymann, 2009, p. 8] Also, FCVs incorporate more process, chemical and electro-technical components such as electro-motors and aggregates for gas management instead of mechanical components (crank shaft, cylinder, piston). Thus, vehicle manufacturers are heavily forced towards backward integration if they want to stay in business. In the end, the supplier landscape of the automotive industry will change significantly once FCVs and BEVs increase market shares.

In conclusion, most standard component suppliers are replaceable; this shortens the suppliers' bargaining power. In addition, the component suppliers do not pose a credible threat to forward integration, but the car industry has the potential for backward integration. The automobile producers are well-known for using the threat of self-manufacture as a bargaining threat. They practice a tapered integration, producing some of their needs in-house and purchasing the rest from outside suppliers. The car industry is also pushing backward integration of FCV specific technology. For example, the first pilot demonstration vehicles were equipped with FCs from component suppliers. In the meantime, the car industry simply bought these suppliers (Daimler/Ballard) or developed their own technology (Toyota, Honda) to gain direct access to this core technology. The car industry has to continue this pathway to ensure future profits.

Vehicle mass production	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	very suitable	suitable	neutral	barely suitable	barely suitable
By 2030	very suitable	very suitable	suitable	suitable	suitable
By 2050		very suitable	very suitable	very suitable	very suitable

Vehicles need **fuel availability** (the criterion of fuel price is evaluated in section 6.4.2). The criterion of fuel availability carries different features: for ICEs, HEVs and partly PHEVs this is, in the first line, the availability of liquid fossil fuels. PHEVs and BEVs need sufficient green electricity to fulfil the societal targets. FCVs rely on 'green' hydrogen, which can be produced from manifold sources and needs to be distributed through an H_2-infrastructure (see criterion on access to infrastructure).

Oil is a finite resource. The IEA only recently announced that peak oil would be reached by 2019; the Delphi expert panel categorised peak oil to the period 2015-2019. The stock of proved crude oil reserves is currently estimated at 1,532 Gbbl (01.01.2012); with current demand, this would last until 2059, see section 3.6. Even if further oil resources could be added to the stock of proved crude oil reserves and unconventional oil resources or CtL could be made available, this additional ‘oil volume’ would need to be sufficient to supply a growing global economy and a growing global population (see *Figure 3-7*), with its increased energy demand (see *Figure 2-2*) at a price competitive to other alternatives (green electricity, hydrogen etc.).

The feasibility of production, storage and distribution of renewable electricity to supply millions of BEVs has been discussed in several studies (see for example Hacker, 2011). In the following it is assumed that the renewable electricity targets of the German government will be reached, thus extension of networks and production capacity will happen in parallel to the extension of the BEV-fleet.

The availability of GCH_2-fuel is inevitably linked to the market success of FCVs. The production of a sufficient amount of H_2 should be possible at all stages of FCV market penetration. Hydrogen is a well known element, central production technologies are mature; decentralised production needs to be further developed at filling stations sites, see section 4.2.4.2. Today, the H_2-production costs through steam reforming are about 1.68 €/kg (2.3 €/MWh natural gas, without logistics, profit, taxes, CO_2-certificates) in Germany. [ChemCoast, 2013, p. 15] R&D on applications of advanced H_2-production technologies using renewable sources is in good shape: with growing H_2-demand, manifold advanced H_2-fuel production technologies offer potential for access to renewable hydrogen energy from various sources. Forecasts on future H_2-fuel prices are optimistic (see Annex 8.2), strongly indicating the good availability also of ‘green’ H_2-fuel.

Availability of fuel[302]	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	very suitable	very suitable	very suitable	very suitable	very suitable
By 2030	suitable	suitable	very suitable	very suitable	very suitable
By 2050		neutral	open	very suitable	very suitable

The market introduction of FCVs will also be influenced by the **availability of resources**. The main bottlenecks could be platinum group metals (PGM) (see section 4.2.4.5) and Lithium. ICE, HEV, PHEV and FCV production rely approximately on the same amount PMG per vehicle. However, exhaust gas cleaning technology and FC technology research are targeted to minimise or substitute PGMs. Progress in this research cannot yet be forecast. HEVs, PHEVs, BEVs and FCVs are also relying on Li-ion batteries. Future Lithium demand will grow, but the supply should be assured until 2050. Availability of PMG and Lithium will be also a question of price, but forecasting is difficult. HEVs, PHEVs and FCVs need both limited resources.

Also, labour should be seen as a supplier. In the recent VDE Trend report “Smart Cities”, the lack of qualified staff was ranked as the second largest obstacle to innovation in the sector (48%) after legal framework conditions (52%). Particularly in the development and production of advanced technologies, the lack of engineers and other qualified staff could become a problem as the innovation strength of the German economy is mainly based on the high education level (71%) and the systematic thinking of the engineers (61%). [VDE, 2014, p. 3] Scarce, highly skilled employees and/or tightly unionised labour can bargain away a significant fraction of potential profit in an industry. The recruitment of staff will become a critical factor to the market implementation of alternative vehicles. In particular, electronic and electrochemical experts are a limited resource.

302 This includes only ‘green’ electricity or hydrogen.

Availability of resources[303]	**ICE**	**HEV**	**PHEV**	**BEV**	**FCV**
Today	very suitable	suitable	suitable	suitable	suitable
By 2030	suitable	neutral	neutral	suitable	neutral
By 2050		open	open	open	open

The German new car market is distributed between **commercial and private customers**. Naturally, buyers are trying to force down prices, or bargain for higher quality and better services. The power of the buyers depends on the relative importance of their purchases from the industry compared with overall business and specific market situations. However, there are so many different fleet buyers, that only very few have a real market power, e.g. The Army (Bundeswehr), Deutsche Post, car hiring companies.

In general, vehicle costs represent *a significant fraction of the commercial buyer's costs*. Thus, commercial fleet operators will be prone to shopping around for a favourable price, i.e. they are very aware of TCOs and the vehicle resale values. As long as H_2FCV-technology is not on the market, there is no indication of the resale value. (The state of FCs could be measured quite easily.) In addition, commercial fleet owners depend heavily not only on cost-efficient but also on *high-quality, reliable* vehicles because they form the basis for their business. Thus, it may be expected that alternative propulsion systems may enter commercial fleets only slowly and in stages following several test runs. Public buyers are obliged to internalise external emission and CO_2-costs to the TCO calculation, making them an interesting customer. Car sharing companies may become an interesting customer, too, since they rarely depend on a rural H_2-infrastructure. They provide mobility to a huge variety of customers and need vehicles in their fleet which distinguish them from competitors, but absolute sales number will be low.

The preferences of *private customers* vary widely. For private customers the purchase of a vehicle is a large, single investment and private buyers are more sensitive to investment costs not TCOs. By 2030, FCVs, BEVs and PHEVs will still be more expensive than respective ICEs in the C/D-segment, see section 6.4.2. Image, brand etc. are other important decision criteria, see *Figure 5-13*. In particular, *privately used cars are a highly differentiated product*, which do not simply allow driving from A to B, but have a high emotional value themselves. These individual buying decisions (a company car may be part of a commercial fleet, but may also represent an individual decision) are highly affected by subjective criteria such as image, status etc. Marketing of alternative propulsion systems will not only have to address these emotional factors, but will also need to provide *full information* to explain technology and TCOs, second hand car markets etc. Experience from the marketing of NGVs demonstrates that this seemingly quite simple task may be difficult to implement, in particular because there are many players involved. However, all alternative propulsion systems will suffer from this constraint.

In this way, *retailers can gain significant bargaining power*, if they are in the position to influence consumer purchasing choice. The dealer may prefer to sell conventional technology, avoiding trouble from the new technology with the buyer and in its garage. However, innovation-ready dealers may achieve recognition far beyond normal business contacts. Additionally, the market introduction of new vehicle technologies also requests the implementation of the related service infrastructure from retailers and garages. For example, Opel en-

[303] Today, no resources bottlenecks exist. Drive trains which depend on Lithium and PGMs have been evaluated neutral by 2030. There exist manifold opportunities to replace Li and PGMs by 2050. The lack of qualified staff applies to all technologies.

hanced its European service network for working with high voltage systems as well as repairing electrical drive-trains in the framework of the market introduction of the Opel Ampera.

Often the *government* is named as the sixth force in industry competition because the government interferes in the market in various indirect and direct ways. Government acts directly as a buyer of vehicles. Administrative regulation supports the procurement of fuel efficient and clean vehicles (see section 3.3), the impact is larger during the market introduction phase because absolute numbers are small. The structural analysis of the H_2FCV-industry in sections 3 and 4 demonstrated how seriously present and future government policies affect the structural conditions of the industry. Government action directly influences the behaviour of suppliers or buyers. For example, the current biofuel regulation supports the use of biofuel blends, see section 3.2.2. Regulation has the power to simply exclude technologies from the market which cannot comply.

Government can also affect the relationship of competing companies or products with one another through regulation, subsidies or other means. For example, the German government intends to prolong the tax incentives for natural gas and LPG, even when the success of this subsidy could not be underpinned by increasing new registration numbers. Research grants such as the “National Hydrogen and Fuel Cell Technology Innovation Programme” of the German government are promoting the hydrogen economy. Safety and pollution standards affect the relative cost and quality of substitutes etc. The key drivers and inhibitors affecting the H_2-fuel market development are summarised in *Figure 6-49*.

<table>
<tr><th>Support</th><th>Inhibit</th></tr>
<tr><td rowspan="3">- Global climate change and the need to reduce GHG-emissions and pollution
- Energy security and the need for energy diversification, energy storage and, for the use of more renewable energy sources, thus to reduce oil dependency
- Growth of global population and economy, need for new clean energy supply at affordable prices, H_2 is potentially available in virtually unlimited quantities and at decentralised locations
- Air quality - need to reduce emissions from vehicles and power plants.</td><td>- Lack of H_2-infrastructure and the substantial costs of building one; high costs of FCVs
- Lack of commercially available, low-cost H_2-production, storage and conversion devices
- H_2-safety issues.</td></tr>
<tr><td>Both Support and Inhibit</td></tr>
<tr><td>- Rapid pace of H_2FC-technology and competing energy sources and technologies
- Availability of relatively low-cost fossil fuels, along with their inevitable depletion
- Simultaneous consumer preferences for both a clean environment and affordable energy supplies
- Dependent on FCV market success.</td></tr>
</table>

Figure 6-49: Key drivers affecting H_2-fuel development

The future strength of the assessed economic, societal and individual forces acting on the market introduction of H_2FCV are summarised in *Figure 6-50*. The results clearly show the incumbent ICE is the most suitable technology to fulfil the requirements today, but already by 2030 this technology will be outdistanced by the hybridised vehicles. By 2030 the gap between alternative and incumbent vehicles will also have narrowed. Until 2050, BEVs and FCVs are the best suited technologies. However, for BEVs important questions such as range, refuelling time and access to public filling stations (technical and organisational aspects) are still unclear. The level of comfort, reliability and durability as well as availability of resources depends heavily on technology development, which could not be forecast by 2050 for most drive trains.

In conclusion, the market entry of H_2-fuel is interlinked to the success of FCVs. The vehicle market is complex. Even if the vehicle market is a globally high volume market, FCV introduction is limited to some world regions due to the large requirements of H_2-

infrastructure development. These markets are primarily USA, Europe, Japan, South Korea, and probably China, totalling annual vehicle sales of around M44 passenger cars. [http://www.oica.net/category/sales-statistics/sales-statistics-2005-2014/] The main shareholders in the market are experienced and fully aware of market barriers and risks. The introduction of FCVs to the market will not increase the total car market size (the Chinese market will grow independently of this), but FCVs will have to replace the well-known, maturely developed ICE-technology, competing at the same time with other electrified vehicle concepts.

On the one hand, FCVs incorporate several new technologies and science disciplines, changing the current value chains of manufacturing and demanding the education of staff. A new filling infrastructure needs to be erected from scratch involving more players. Costs for the market introduction of vehicles and infrastructure will be tremendous and profit perspectives will be low in the short- to midterm prospect. Also, the users' TCOs will be larger than for incumbent technologies for a long time. Despite market introduction of NGVs, there will be no intermediate solutions such as bivalent vehicles. Infrastructure and vehicle implementation must go hand in hand and has to be realised in a particular region, e.g. Germany, within a short period of time (less than 10 years) to be successful.

On the other hand, H_2FCV-technology has the potential to ensure individual, comfortable mobility in line with the future environmental, climate and energy security requests of the society as articulated today. Therefore, the market penetration of H_2FCV-technology will need strong societal support and, in consequence, good governmental regulation. Thus, the main drivers for FCV and H_2-fuel development are reliable and enforced political targets on combating climate change and supporting energy diversity and air quality. The CO_2-fleet targets, beyond all critics, have been proved as a technically feasible and effective as well as widely accepted management tool. However, public change in the perception of the environmental problems or heavy economic distortions could result in less strict climate targets, re-entering into the use of nuclear energy or an exit from the renewable energy targets in the EU/Germany etc. In addition, external events such as another financial or oil/energy crisis would reduce the readiness to pay for climate protection or increase competitiveness of hydrogen dramatically. Also, the frequency and extent of damage from future weather extremes affecting, in particular, the Western hemisphere, may change public attitude towards climate change.

Each change in the framework conditions would have its specific consequences for the market introduction of green hydrogen and FCVs. In particular, nature and scope of the latter external events could not be forecast, but they will exist as an important driver or inhibitor for H_2FCV technology introduction.

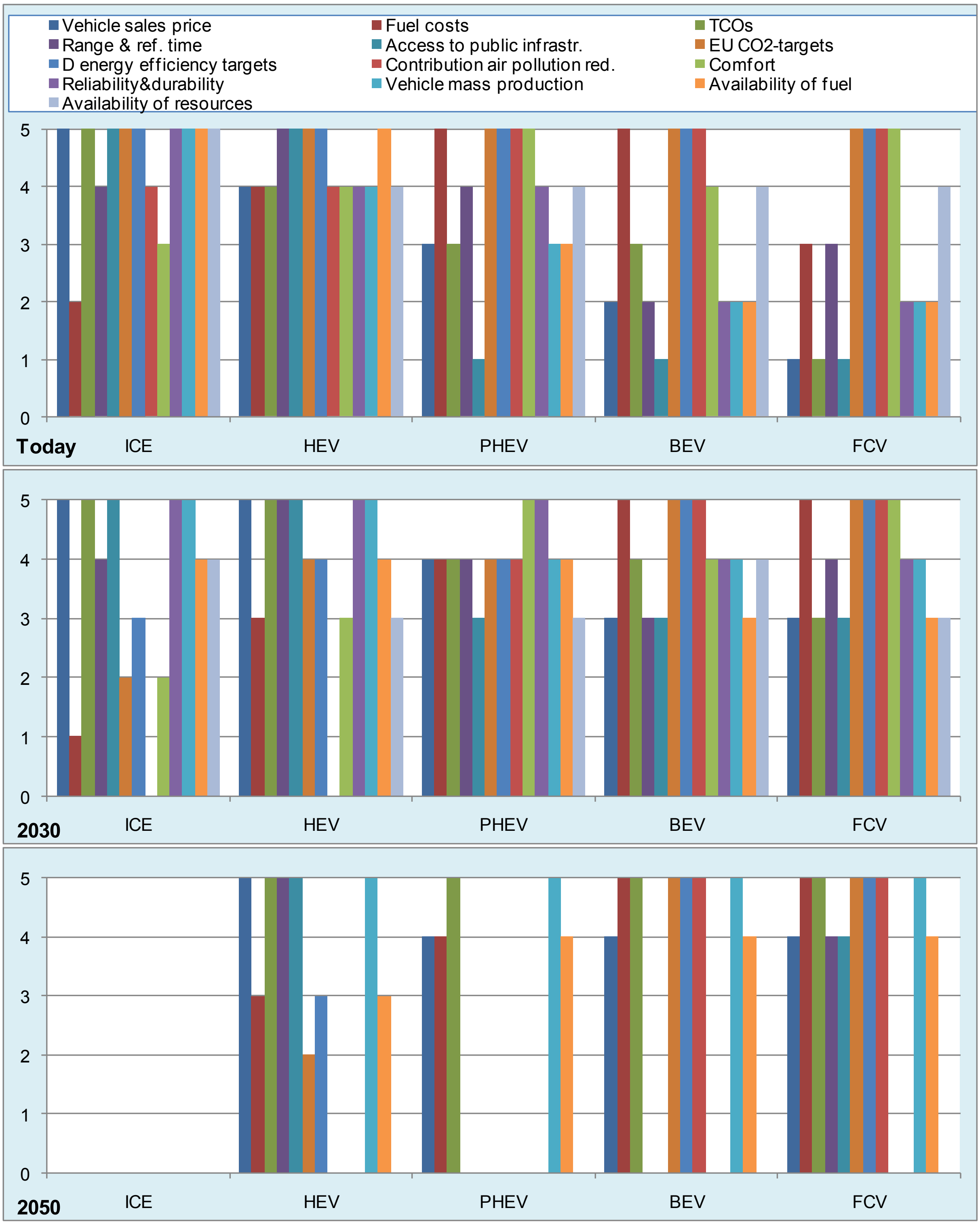


Figure 6-50: Summary evaluation of the main forces affecting H_2FCVs

7 The market introduction process

In the following, a possible pathway for the market penetration of H_2FCV-technology is outlined. It is assumed that there is an intensive and sustained societal consensus (at least in the EU) on the urgent need for action to limit CO_2-concentration in the atmosphere to achieve the 2DS target. According to COM2011(112) the 2DS translates to an overall EU climate reduction target of 80% (below 1990 levels). The transport sector is expected to contribute with a 60% GHG-reduction. In its latest communication, COM(2014)15 on the climate policy framework until 2030, the EC confirmed that the current passenger vehicle GHG-reduction tool, i.e. the approach of setting fleet limits, is efficient and suitable. (This procedure is also harmonised with the US market, setting a consistent legislative framework in which the European industry may compete and develop a ‘green’ car market.) The 2DS target translates to the achievement of at least 40gCO_2/km for the EU’s car fleet.

In principle, clean car technologies, which could attain values of less than 40 gCO_2/km, are ready for market implementation. The incumbent ICE-technologies bear the potential to decrease emissions to the 2021 limit of 95 gCO_2/km (also without the use of biofuels), but probably not far beyond. The extent of future use of biofuels is unclear due to the sustainability debate and heavy competition with stationary use of biomass. New technologies comprise all kinds of electrified vehicles, in particular BEVs and FCVs. BEVs and FCVs offer the option of using a multitude of renewable energy sources, e.g. renewable electricity, which, in general, do not compete with food production. BEVs and FCVs also provide a largely increased energy efficiency.

A recent IEA study shows an upward trend in transport fuel use and GHG-emissions around the world without strong policy intervention to change course (also see section 2). For example, the 4DS in the IEA Energy Technology Perspectives 2012 shows a near doubling of transport CO_2 from 8 Gt in 2010 to about 14 Gt CO_2 in 2050, whereas a 2DS is consistent with reducing these emissions to 6 Gt CO_2, i.e. 25% below the 2010 level and less than half the 2050 level in the 4DS. *Figure 7-1* shows an IEA scenario of passenger LDV sales which would be suitable for supporting the 2DS-target. In this scenario BEVs, PHEVs and FCEVs together account for nearly three quarters of vehicles sales in 2050. [Fulton, 2013, p. 4]

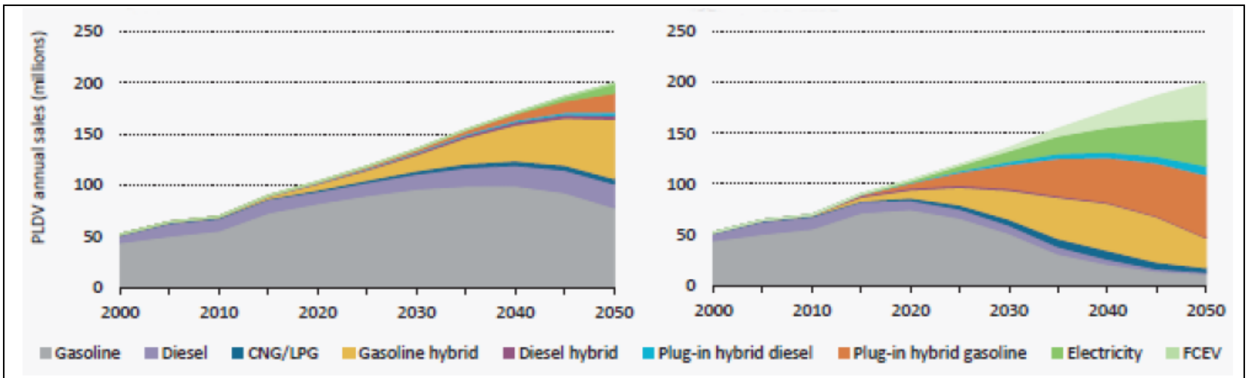


Figure 7-1: Global portfolio of technologies for passenger LDVs to achieve IEA 4DS (left) or 2DS (right) [Fulton, 2013, p. 4]

The detailed share between BEVs, PHEVs and FCVs does not really matter as long as the CO_2-target under real driving conditions is met (this restricts PHEVs mainly to short distance driving). The customer, due to their specific interest, will determine the share between BEVs and FCVs. Important car-makers (at least GM, Toyota, Honda, Hyundai) argue that FCVs are the only technology currently available that provide essential characteristics attributed to current car technology, i.e. space, comfort (heating and air conditioning etc.) and a range of more than 500 km. There is no convincing argument for applying BEVs in larger cars assuming an area-covering H_2-fuelling network were available. (Several studies have shown that TCOs of BEVs and FCVs would be quite equal beyond 2030.)

Figure 7-1 also shows that the clean vehicle sales will account for a relatively small share until 2030, i.e. providing only a negligible impact on clean vehicle cost and GHG-reduction. Newly registered conventional vehicles are already determining the vehicle fleet for 2020, since the automobile is one of the most long-term investments of the average consumer (just after real estate). The simulation of different market introduction scenarios in *Figure 5-19* clearly showed that for a significant impact of clean vehicles to GHG-reduction, it is imperative to start selling these vehicles very soon, because it takes several decades of steady increase in their collective sales share to achieve a significant proportion of the vehicle stock. However, technology still needs to undergo learning and market penetration processes, see section 5.4.

Customers and manufacturers will soon need clear signals from the policy on the future development of taxes, incentives and standards to get ready to invest in clean vehicles. The European Parliament endorsed a target of 68-78 gCO_2/km from 2025 in 2014, but longer targets need to be revealed soon. Only in this case, could serious numbers of zero emission vehicles be put in use between 2020 and 2030, which could pave the way for an overall GHG-reduction target of 60% by 2050, despite increases in transport volume. In the Delphi-analysis (question 25), none of the experts contradicted the assumption that the car will remain the most important passenger transport means. Also, the current trends in modal shift do not indicate a trend away from individual transport by car, even if the younger generation may show a more differentiated attitude towards the private car. It is therefore all the more important that the GHG-footprint of cars is reduced.

However, the problem of these new electrical propulsion systems is that in the near term, they are expensive. In order to become more economically attractive in the longer term, it will require someone to pay for the near term incremental costs, the **“buy-down” costs** of these vehicles. In addition, the market transformation to EVs requires drastic change in vehicle technology as well as in the related energy production, distribution and fuelling infrastructure. The latter is particularly true for the market introduction of H_2FCVs. The timeline for these changes will have to respect regular vehicle and equipment substitution cycles to keep costs affordable. Current vehicle lifetimes are about 13 to 15 years.

Furthermore, H_2-fuel used for the storage of alternating renewable energy could support the transition of the energy sector and contribute towards compliance with GHG-targets in the stationary and domestic sector. Fraunhofer (see section 4.2.4) calculated a principal feasibility scenario with M28 FCVs in use in Germany to support a complementary H_2-vehicle fuel / H_2-energy storage system by 2050. [Grube et.al., 2014, p. 23] Even if the achievable FCV-number may be lower in Germany, the management of H_2FC-technology introduction will be a complex and expensive undertaking. The stakeholder responsible for organising the framework conditions is the government; concrete work could be carried out by organisations such as CEP and H_2-mobility.

The recent Fraunhofer ISI study providing scenarios for the market launch of BEVs for the German market until 2020 clearly demonstrates what happens if government does not provide mandatory leadership and leaves the introduction of clean vehicles to the market forces. Fraunhofer ISI evaluated three scenarios for the market launch of electric vehicles. The timeframe of the analysis was limited to the year 2020, thus covering a period of only six

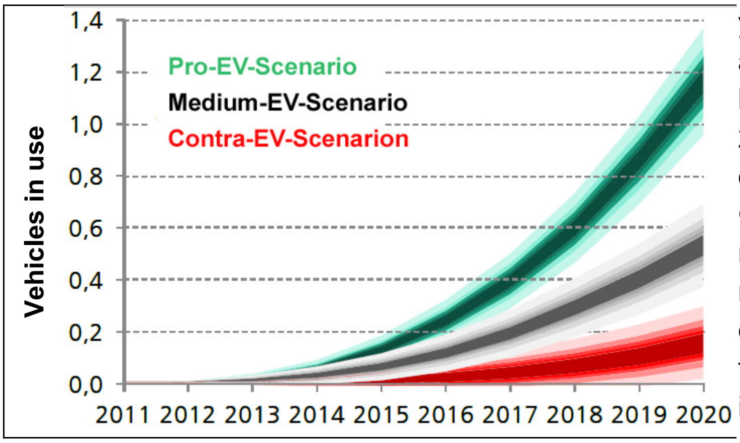


Figure 7-2: Market launch according to TCO-decisions [Plötz, 2013, p. 119]

years.[304] Even so, the three scenarios applied resulted in a large bandwidth between k50 and M1.4 EVs in use by 2020 due to strong dependence on external framework conditions. A German market forecast of FCV-numbers and H_2-infrastructure implementation would be even more complex due to the much longer timeframe and still missing concrete information on FCV-characteristics and FCV-prices.

It would need at least an approximate constant structural relationship between the relevant variables (see section 6.4) for any reliable forecast. In reality, the future is unknown and structural breaks as well as unforeseeable events will happen. In the long-term even small changes may uncover large effects. Therefore, this work withdraws from a forecast of detailed FCV- and H_2-station figures, but describes a pathway that could lead to the successful implementation of H_2FCVs:

1) FCV as well as H_2-production and distribution technologies have reached a high degree of readiness for market introduction: the patent analysis, publications from the industry and evaluation from independent institutes underscore the high level of technical readiness achieved in the meantime, see sections 4.2.4.5 and 6.2.2. The patent analysis also showed that the basic research phase is coming to an end. The FCV proprietary knowledge is in the hands of those companies which are currently preparing for market introduction. i.e. Toyota, Honda, Hyundai and Daimler. In particular, the Japanese companies are forcing market introduction; other Japanese companies active in stationary and mobile FC-applications and their substantial experience with HEV-technology may support this process. It is practical experience and cost reduction that remain an issue.

2) A stable, predictable and demanding legislative GHG-reduction framework along with state incentives will encourage industries and customers to invest. During the past ten years the EC has experimented with different policy measures such as the ETS, fleet targets, biofuels quotas, taxes and other financial incentives. In parallel, a comprehensive statistical and monitoring system was implemented, refined and verified to control the effectiveness and impact of various measures. The recently published trends of the energy,

304 The study used the driving profiles of several thousand conventional vehicles as well as technical and economic data on vehicle size and price, brand, fuel consumption and type, exhaust emissions, range, number of models available on the market and readiness-to-pay for innovation. It was assumed that users would decide according to the TCO-criteria. In general, a high level of electric driving (80%) and at the same time, a high annual mileage (more than 15 k-km), have been identified as the decisive criteria for economic efficiency of EVs. REVs and PHEVs will make up three quarters of the EVs. The high share of garages or own parking area available, the large annual mileage and healthy financial situation make fully employed private individuals from rural areas or small/mid-sized towns an interesting private consumer group. A willingness to pay a premium of 30% for an EV has been assumed for innovators (0.5% of the driving profiles); 15% for early adopters (1% of the driving profiles) and another 10% for the late majority (48% of the driving profiles) and 1% for the laggards (50.5% of the driving profiles). Also, commercial fleets are interesting customers due to the high share of predictable routes and strong orientation at TCOs during the procurement process. The sensitivity analysis showed a low effect of the reduced EV's model portfolio, but a high influence of TCOs and willingness to pay. [Plötz, 2013, p. 1-8]

transport and GHG-emissions by 2050 clearly show the suitability of the fleet standards in reaching EU GHG-targets, but it also proved that the current measures are not sufficient to achieve the transport 2050 GHG-targets. Overall, transport GHG-emissions are expected to increase by 19% until 2050 compared to 1990 (RS2013); the final transport energy demand is expected to even increase by 30% during the same period (including freight transport), see sections 2.1 and 2.4.

The EC assessed three GHG-reduction scenarios (35%, 40%, 45%) to be achieved by 2030. This Impact Assessment confirmed the conclusions of the Energy Roadmap 2050, *"namely that the costs of a low carbon transition do not differ substantially from the costs that will be incurred in any event because of the need to renew an aging energy system, rising fossil fuel prices and adherence to existing climate and energy policies."* [COM(2014)15] Thus, if society is anyway presented with large investments in the energy system, decisions should not be steered by the strongest lobbying group, but by a societal consensus on future targets on energy, climate and transport policy. The German and EU-targets for using renewable energy in the transport market and GHG-reduction (see Annex 8.2) have been defined in the democratic process, including participation procedures for interested stakeholders. The long-term targets still have to be translated into concrete, legal requirements or other measures. The EC is leading this process, see section 3.1. This process will result in the ***exclusion of all technologies which will not be able, due to technical and economical facts, to contribute to target compliance*** (technology open framework).

The Delphi-experts highlighted the importance of strict government standards (incl. a rise in CO_2-emissions costs) (question 27) and the role of innovative technologies (question 26) as a tool against climate change. However, they did not expect that the customer would be prepared to pay a premium for "green" products and services of up to 20%.

3) H_2FCV-technology has a high degree of compliance with societally-desired targets (in arbitrary order): freedom of movement, right for mobility, protection from health impact caused by vehicle emissions, climate protection, sustainable growth, energy security.

4) Implementation of an H_2-infrastructure and stricter CO_2-fleet standards could lead to success of H_2FCV-technology. The DLR Vector 21-study (see section 5.3.3.2), analysed the impact of the driving factors CO_2-regulation, oil price and availability of H_2-infrastructure on the market introduction of H_2FCVs until 2040. The result was clear: only the combination of "H_2-infrastructure available" and CO_2-fleet limit reduction to 40 gCO_2/km increases the share of H_2FCV-registration numbers to 7% by 2040, see *Figure 7-3*. According to the Delphi-analysis suitable tools for providing an H_2-infrastructure would include the public co-funding of H_2-infrastructure beyond the first demonstration projects (question 39) and financial support for the production of regenerative hydrogen (question 52). In addition, international mandatory CO_2-standards (question 43), stricter CO_2-fleet standards (question 40) and the inclusion of transport within the ETS (question 41) could promote H_2-fuel and FCVs.

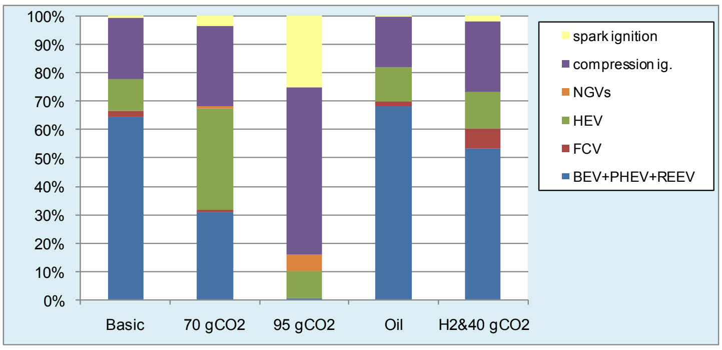


Figure 7-3: Impact of various driving factors on fleet portfolio by 2040 [own depiction, Brokate, 2013, p. 52]

It would be the role of the government to support the implementation of those technologies which support the societal targets. In 2013 a draft Directive was published by the Council that asks EU Member States to ensure that specified numbers of H_2-stations are built by 2020 (see section 3.2.2 and the US Clean Fuel Outlet Programme). The input of the mineral oil industry for greening transport is currently quite low compared to the efforts of the car industry. In addition, the EC is considering (COM2014(15)) skipping the biofuels quota - this would release the mineral industry further.

The balanced positioning of the H_2-stations may be organised by H_2-mobility in Germany. A midsized H_2-filling station with two fuel pumps is designed to serve 800 FCVs and sells about 120 MgH_2/a.[305] The cost of adding one H_2-dispenser to a filling station is currently at least 700 k€, thus the cost for k1 filling stations would add up to about 700 M€. Then, the filling station density would be even higher than the current CNG-station density. In particular during the market launch phase, a high increase in FCV-numbers is necessary to utilise the existing network. In addition, investment in H_2-production would be necessary, see section 4.2.4.2. With current fuel consumption and projected fuel costs between 6.70 €/kgH_2 (Fraunhofer using wind energy and electrolysis) and 4 USD/kgH_2 (US DOE) delivered and dispensed by 2020, the fuel costs per 100 km without taxes would be very reasonable. The current fuel tax exemption could be decreased in parallel to decreasing H_2-production costs due to scale effects. An orchestrated investment plan is required to build up the first critical mass of H_2-supply. This plan was developed by the H_2-mobility initiative for the German market, also with an outlook for the European markets. The first chapters are already in the implementation stage. Manufacturers are preparing for FCV- and H_2-station production. More manufacturers and regions are continuously extending the CEP.

Furthermore, FCs are revolutionising the production of electricity and thermal energy also for stationary applications. They offer a key chance for shifting from fossil fuels to renewable hydrogen and will also provide a large gain in vehicle and other application efficiency.

5) Reduce high FCV-costs by scale effects and further technology development. R&DD (see sections 4.1, 4.2.4.5 and 5.4) activities result in technical progress. Technical progress allows certain ***technical targets*** to be achieved, i.e. the reduction of the Pt-loading of the catalyst or the improved gravimetric density of the 70-MPa-storage systems, to mention only a few examples. Ultimately, R&DD is an enabler for the achievement of ***H_2- and FCV-price targets*** which contributes to customer acceptance. Annex 8.2 shows performance, infrastructure and FCV-targets set by various organisations.

It is assumed that market competition between substitution products is decided mainly by the factors summarised in Figure 6-50. The active marketing of the H_2FC-technology by stakeholders and growing public acceptance of the H_2FCV-technology will further trigger market demand. The Delphi experts scored highly for the guiding effect of sustainable development and environmental consciousness on the consumer side (question 28). Conversely, this was not reflected in the readiness to pay (question 30). Stricter CO_2-car standards will increase the costs for incumbent technologies and will help to close the cost gap, in particular after 2021. However, over the next 20-30 years, no single power-train will satisfy all key criteria for economics, performance and the environment, see section 6.4.

Industry stakeholders are currently pushing towards H_2FC-market entry between 2015 and 2017. Nevertheless, the shift away from over 120 years of application of the internal combustion engine to the use of electrical propulsion systems is a turning point in an era.

[305] Assuming an annual mileage of 15 k-km and a fuel consumption of 1 kgH_2/100 km.

Inertia within the industry will be mammoth, since largely abandoning the existing range of models and technologies would not be without substantial financial losses for manufacturers. It should be taken into account that even minor developments in vehicle equipment take about eight years for a larger market penetration. [Schindler, 1997, p. 43] For example, unleaded petrol was introduced in Germany in 1984. Only in 1996, was the distribution of unleaded super abandoned due to decreased demand.

The results of section 6.4 suggests that no single technology alone will be able to conquer the future market, but a move from a single power-train (ICE) to a portfolio of power-trains in which BEVs, FCVs and other alternative fuels and technologies play a complementary role is likely. The car manufacturers will continue to develop those technologies with the expected highest (global) market success chances. Also, niche markets may be supplied, but effort will depend on size, importance and potential of the market.

This work shows that H_2FCV-technology has a good potential to fulfil the future requirements of car customers in the wealthy, industrialised countries, see Figure 6-50. In general, BEVs are better suited to smaller cars and shorter trips with PHEVs providing an attractive solution for short trips and occasional longer trips. However, for consumers who prefer larger cars and drive longer distances, FCVs have clear benefits in a CO_2-constrained world. In the EU, this segment represents around 50% of cars driven and can therefore justify a dedicated H_2-infrastructure. The value of the FCV over alternative power-trains in terms of TCO and emissions (including the cost of the hydrogen infrastructure) could be positive beyond 2030. The economic gap prior to 2030 is almost completely determined by the higher FCV purchase price, not by the cost of the H_2-infrastructure. If a consumer segment prefers the FCV, the cost of the infrastructure (5% of the TCO) will not be prohibitive to its roll-out. [McKinsey 2010, p. 5-6]

In any case, **for the fulfilment of political and legal targets on CO_2-reduction BEVs and FCVs are currently the only available, widely discussed, suitable solutions**. Thus, consistency and stringency of the EC and the German government in the implementation of their targets will determine market success of FCVs. The window of opportunity is brief. There is also a danger that Europe will lose its technological leadership as other international markets gain ground. The European Commission confirmed “the global trend towards sustainable transport shows that the European automotive industry can only remain competitive by leading in green technologies”. [McKinsey 2010, p. 32]

8 Annexes

8.1 Overview of the most important fuel cell and hydrogen technology standards

ISO/TS 14687-2:2008: Hydrogen fuel - Product specification - Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles
ISO 15869:2009 Gaseous hydrogen and hydrogen blends - Land vehicle fuel tanks: Type 1: Metal fuel tanks; Type 2: Hoop-wrapped composite fuel tanks with a metal liner; Type 3: Fully wrapped composite fuel tanks with a metal liner; Type 4: Fully wrapped composite fuel tanks with no metal liner
ISO 17268:2006: Compressed hydrogen surface vehicle refuelling connection devices
ISO 19078:2013: Gas cylinders - Inspection of the cylinder installation and requalification of high pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles
ISO 20100:2008: Gaseous hydrogen - Fuelling stations
ISO 22734-2:2011: Hydrogen generators using water electrolysis process - Part 2: Residential applications
ISO 23273-1-2-3:2006: Fuel cell road vehicles - Safety specifications - Part 1: Vehicle functional safety, Part 2: Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen, Part 3: Protection of persons against electric shock
ISO 6469-1-2-3-4: Electrically propelled road vehicles - Safety specifications: Part 1: Onboard rechargeable energy storage systems, Part 2: Vehicle operational safety means and protection against failure, Part 3: Protection of people against electric shock, Part 4: Post crash electrical safety requirements
SAE J1766: Recommended practice for electric and hybrid electric vehicle battery systems crash integrity testing, 2005
SAE J1797: Recommended practice for packaging of electric vehicle battery modules, 2005
SAE J1798: Recommended practice for performance rating of electric vehicle battery modules, 2008
SAE J2578: Recommended practice for general fuel cell vehicle safety, 2014
SAE J2579: Standard for fuel systems in FC and other hydrogen vehicles, 2013
SAE J2600: Compressed hydrogen surface vehicle refuelling connection devices, 2012
SAE J2601: Fuelling protocols for light duty gaseous hydrogen surface vehicles, 2014
SAE J2719: Hydrogen fuel quality for FCVs, 2011
SAE J2760: Technical information report for pressure terminology used in fuel cells and other hydrogen vehicle applications, 2011
SAE J2799: Hydrogen surface vehicle to station communications hardware and software, 2014
HGV 4.1: Hydrogen dispensers
HGV 4.2: Hose and hose assemblies for hydrogen vehicles and dispensing systems
HGV 4.3: Fuelling parameters for hydrogen dispensing system
HGV 4.4: Breakaway devices for hoses used in hydrogen vehicle fuelling stations
HGV 4.5: Priority and sequencing equipment for gaseous hydrogen dispensing systems
HGV 4.6: Manually operated valves used in gaseous hydrogen vehicle fuelling stations
HGV 4.7: Automatic pressure operated valves for use in gaseous H_2-vehicle fuelling stations
HGV 4.8: Hydrogen gas vehicle fuelling stations compressor
HGV 4.9: Fuelling system guideline
HGV 4.10: Performance of fittings for compressed hydrogen gas and hydrogen rich gas mixtures

Figure 8-1: Overview of the most important fuel cell and hydrogen technology standards

8.2 H_2FCV technology and framework conditions development pathway

	1996/2000	2001/2005	2006/2010	2011/2015
Industry announcements / Vehicle numbers	Start of serial production by 2004-2005 [Chap. 6.1]	Start of serial production by 2010-2015 [Chap. 6.1]	Start of serial production by 2011/2015 [Chap. 6.1]	Start of serial production by 2014/2017 • Daimler B F-Cell leased out since 2012 • k5 FCVs by 2015 [Annex 8.3]
Infrastructure deployment		• Inauguration of Messedamm in 2004 [Chap. 4.1.3]	• Inauguration of Heerstraße in 2006 [Annex 8.3] • 27 H_2 stations available in Germany in 2010 [Annex 8.3]	• 32 H_2-stations in Germany in 2013 [http://www.netinform.net/h2/H2Stations/H2Stations.aspx#liste; 06.10.2013] • 50 H_2-stations by 2015 (D) [Chap. 4.1.3]
Political targets & legal requirements		• German sustainability strategy: use of H_2FCs defined as renewable energy in 2004 [Chap. 4.1.3]	• Green paper: 12% renewable energies in 2010 [Chap. 3.1]	• Biofuel quota of 3% by 2015 (D) [Chap.3.2.2] • $PM_{2.5}$< 25 µg/m³ by 2015 (EU) [Chap. 3.1] • Kyoto:-21% CO_2, 2008-2012 (D) [Chap.3.1]
RDD activities	• Foundation of VES in 1998 [Chap. 4.1.3] • FP5: 145 M€ for H_2FC research (1998 – 2002) [Chap. 4.1.1]	• VES decision on H_2-fuel in 2001 [Chap. 4.1.3] • CEP foundation, 2002 [Chap. 4.1.3] • Start CUTE project, 2003 [Chap. 4.1.1] • FP6: 314 M€ for H_2FC research (2002 - 2006) [Chap. 4.1.1]	• Establishment of the NIP, 2006, H_2-mobility initiative founded 2009 [Chap. 4.1.3] • DOE H_2FC budget: 1.254 GUSD (2006-2010) [http://www.hydrogen.energy.gov/budget.html, 10.10.2013]	• Transformation of the H_2-mobility initiative into a joint venture in 2012 [Chap. 4.1.3] • FP7: 470 M€ for H_2FC research (2006-2013) [Chap. 4.1.1] • DOE H_2FC budget: 497 MUSD (2011-2014) [http://www.hydrogen.energy.gov/budget.html, 10.10.2013]
H_2 and FC price targets			• 8.50 €/kg, incl. VAT (dispensed at CEP-station)	• 9.50 €/kg, incl. VAT, renewable H_2 (dispensed) • 0.5-0.8 USD/l_{eq} by 2015 (DOE) [Chap.4.2.4.2] • H_2 from central electrolysis < 3 USD/kg at plant gate by 2015 (EERE) [Chap. 4.2.4.2] • H_2 at filling station < 5€/kg [Chap. 4.2.4.2] • Pt-loading < 0.2 mg/kW by 2015 [Chap.4.2.4.5] • Gravimetric capacity 70 MPa system > 5.5%, cost storage system < 2USD/kWh by 2015 (DOE) [Chap. 4.2.4.4]
Other H_2FC technology drivers	No H_2 and FCV market available			• Scandinavian and Austrian H_2-corridors progressed; Leasing rate of mid-class vehicle ~ 700 €/month (2013, D)

	2016/2020	2021/2030	Beyond 2030
FCV targets	• k150 FCVs by 2020 (D) [Annex 8.3]	• M1.8 FCVs by 2030 (D) [Annex 8.3]	
Infrastructure deployment	• 400 H_2-stations or 60% covering of the population by 2020 (D) [Chap. 4.1.3]	• k1 H_2-stations or 100% covering of the population by 2030 (D) [Chap. 4.1.3]	
Political targets & legal requirements	• Biofuel quota of 4.5% by 2017 and 7% by 2020(D) [Chap.3.2.2] • 2012: MKS-1st commercial FCV on market by 2017 (D); 10% energy saving transport [Chap. 4.1.3 • 2007 Merseburg: 40% less GHG by 2020 (D) ; IEKP: 20% less transport GHG by 2020 (D) [Chap. 4.1.3] • 95 gCO_2/km car fleets by 2020 (D) [Chap. 3.2] • 20% $PM_{2.5}$ level less than 2010 by 2020 (EU) [Chap. 3.1] • EC's 2020 goals (20% GHG-reduction, 20% renewable energy sources, 20% reduction in primary energy use) [Chap. 3.2] • Green paper: use of 20% fuel substitutes (biofuels, natural gas, hydrogen) in 2020 [Chap. 3.2]	• 68 – 78 gCO_2/km by 2025 (EU) [Chap. 3.2.1]	• 2007: Merseburg: 50% green electricity by 2050(D) [Chap. 4.1.3] • 2012: MKS: 40% transport energy saving by 2050 (D) [Chap. 4.1.3] • White paper: 60% reduction of transport GHG-emissions while supporting mobility by 2050 [Chap. 3.2]
RDD activities	• FP6 – FC cost ompetitive with conventinal drives, 2020, [Chap. 4.1.1]	• Advanced renewable H_2-production (photo-chemical, algae)	
H_2 and FC price targets	• H_2<4 USD/kg produced and distributed by 2020 (EERE) [Chap. 4.2.4.2] • FC costs: 16-98 €/kW, 43.8 ct/km TCOs by 2020 [Chap.4.2.4.5]	• 3.50 - 5.50 €/kg H_2 before taxes [Chap. 4.1.3] • 36.5 ct/km TCOs by 2030 [Chap. 4.2.4.5] • After 2025, TCOs of HEVs, PHEVs, BEVs, FCVs converge strongly-or earlier with incentives [Chap.4.2.4.5]	• Beyond 2030 FCVs have a TCO advantage over BEVs and PHEVs in the larger segments [Chap.6.4.2]
Other H_2FC technology drivers	• NEP target of M1 electrif. vehicles supports development of critical electrical and control components (D) [Chap. 4.1.3] • US EPA fleet standards push FCV technology • Peak oil is reached [Chap.6.3.2.3]	• US EPA fleet standards push FCV-technology by 2025 • Weekly crude oil spot price 200 USD/bbl; Cities further restrictions for environ. Zones [Chap.6.3.2.3]	• Net impact on employment of +M0.2-0.4 labour years p.a. by 2030 [Chap. 4.1.1]

8.3 Overview of key media announcements on H_2FC-technology progress

10/1997	Toyota presented a PEMFC-car with hydride storage, mileage 250 km. [WSS 1/97][306]
Q1 1997 09/1997 05/1999	Announcement of H_2-project with GH_2- and LH_2-production at Munich airport within the framework of “Expo 2000”. Start of filling station construction at Munich airport. Inauguration of public filling station for CGH_2 and LH_2 at Munich airport. [WSS 1/97,WSS 6/97, WSS 2/99]
Q2 1997	The first H_2-bus licensed for traffic on public lines (MAN SL, no restriction on passenger numbers, test start 05/1996) reached 0.012 Mkm line operation without incident in Erlangen - good driver and passenger acceptance. [WSS 2/97]
Q2 1997	After completion of a large-scale test at Rügen, the German Federal Ministry for Education and Research announced that BEVs will remain a niche product and hydrogen or FCVs will have a chance to become a real alternative to conventional vehicles. [WSS 2/97]
05/1997	Presentation of the NEBUS. [WSS 3/97]
05/1997	BP accepted anthropogenic CO_2-increase and climate change. [WSS 3/97]
Q3 1997	Daimler announced FCV serial production for 2004/2005. [WSS 5/97]
09/1997	The Chicago (Illinois, USA) Transit Authority added the first of three FC-(Ballard)-powered buses to its service fleet for testing on public transit routes for two years. [Bokow, 1997]
12/1997 2000	Opening of H_2-filling station to supply six converted vans within the area of the Hamburg Gasworks. Final commissioning of all six Mercedes Sprinters in 2000. [WSS 6/97, WSS 1/00]
Q4 1997	Shell founded “Shell International Renewables” investing 500 MUSD in 5 years. [WSS 6/97]
Q4 1997	The Berlin gas company GASAG announced natural gas as a bridging fuel for H_2-economy. [WSS 6/97]
Q4 1997	Inauguration of the first FC-forklift in Neunburg. [WSS 6/97]
Q1 1998	John Smith, CEO of GM, predicted the phasing out of the ICE by 2020/2030 and announced GM FCV would be on the market no later than 2004. [WSS 1/98]
Q1 1998	Daimler/Ford/Ballard alliance announced FCV-systems with an annual production of M0.1 units for 2004. [WSS 1/98]
03/1998	Opel presented 50 kW methanol FC station wagon “Sintra” at the Geneva Auto Salon. [WSS 2/98]
03/1998	Foundation of the Swedish Hydrogen Association. [WSS 3/98]
03/1998	Ford and mobil united to develop a hydrocarbon reformer. [WSS 2/98]
04/1998	Foundation of the French Hydrogen Association. [WSS 3/98]
05/1998	First presentation of the “VES”, see section 4.1.3. [WSS 3/98]
08/1998	dbb and Shell united in a project for the development of reformer technology. [WSS 4/98]
Q3 1998	Operation of hybrid 5 kW AFC / battery taxi in London. [WSS 4/98]
Q3 1998	Berlin and Hamburg public bus operators announced conversion of diesel bus fleet to hydrogen starting in 2005 (as far as suitable technology is available). Both companies rejected the use of natural gas as an intermediate solution. [WSS 4/98]
Q3 1998	Opel added the “Global Alternative Propulsion Center” in Mainz-Kastel to the US GM research centres in Warren and Rochester. [WSS 4/98]
Q3 1998	Sulzer-Hexis AG announced the market introduction of 1.5 kW_{el} SOFC in 2001. [WSS 4/98]
09/1998	Opel presented a 50 kW FC Opel Zafira at the Paris Autoshow. FCs were seen as having the largest potential for high volume production of all alternative propulsion systems, readiness for markets is aspired to for 2004. [WSS 5/98]
Q4 1998	General Electric and PlugPower founded “GE Fuel Cell Systems”. [WSS 5/98]
Q4 1998	Foundation of the “US Fuel Cell Council” (USFCC). [WSS 6/98]

[306] The German Wasserstoffspiegel (WSS) is published six times a year by the DVGW on its homepage: http://www.dwv-info.de/aktuelles/haupt_wspiegel.html. It documents the development in the H_2-economy since the mid of the 1990s. In the following, reference is given to the concrete issue: *WSS Issue/Year* directly in the table, not in the reference list.

01/1999	Inauguration of the first public CGH_2-filling station in Hamburg. Shell Germany's Member of the Board Vahrenhold denominated hydrogen as the most important energy carrier of the future replacing mineral oil and natural gas in the long-term. Shell expected that up to 50% of the 2050 energy demand will be covered by alternative sources such as wind, solar and hydropower. Half thereof will have to be transformed to hydrogen. In the beginning, the regenerative H_2-production will not be sufficient to keep up with the market demand, thus it will be necessary to enlarge conventional H_2-production capacities. [WSS 1/99]
01/1999	AirLiquide took over the German gas business from the British BOC-group now owning the 240 km hydrogen pipeline network in North-Rhine-Westphalia. [WSS 1/99]
01/1999	Natural disasters caused economic damage of 90 GUSD in 1998. This is more than the total damage of the 1980s. Also, the total number of events at 700 was extremely high, added to that, the share of atmospheric extreme events has been striking, indicating that global warming increases the danger of natural disaster in several world regions. [WSS 1/99]
03/1999	Presentation of Necar4 (70 kW, maximum speed 145 km/h, 100 l LH_2-tank volume). *Confirmation of start of serial production in 2004* (after an investment of 1 G€). [WSS 2/99]
04/1999 04/2000 02/2001	Co-operation between BMW and Delphi Automotive Systems for the development of FC APU for H_2- or conventional vehicles and investigation of petrol reformer technologies. [WSS 3/99]; Renault joined a consortium of BMW and Delphi to develop a SOFC APU. [http://www.highbeam.com/doc/1G1-62708040.html; 27.06.2011] BMW presented a 5 kW SOFC APU reforming petrol at ca. 800°C to hydrogen; the efficiency is nearly the double of that of an engine, generator and battery system. [WSS 1/01]
06/1999	Foundation of the "Ford Forschungszentrum Aachen", William Clay Ford Jr. announced that *Ford shares the serial market introduction plans of Daimler*. [WSS 3/99]
06/1999	Ballard, Petro-Canada and Methanex Corp. united to implement a methanol infrastructure around Vancouver. Ballard CEO Firoz Rasul announced that the vehicle manufacturers *hope to produce up to 25% FCVs in 2010*. [WSS 3/99]
Q2 1999	*Honda* announced investment of 380-470 M€ in zero-emission vehicle technology until 2003 using small FCs the company has developed. Takeo Fukui, Head of R&D department, expected than *FCVs will overtake petrol vehicles in 20 to 30 years*. [WSS 3/99]
Q3 1999	Canada invested 30 M$ in a "National Fuel Cell Research and Innovation Initiative". The university of British Columbia received "National Fuel Cell Research Facility". [WSS 4/99]
10/1999	*Mitsubishi* presented an FC concept car at the Tokyo Motor Show and announced *market entry for 2005*. [WSS 5/99]
Q3 1999	US Congress authorised 25 MUSD for the H_2-programme of the year 2000 budget. [WSS 5/99]
Q3 1999	Shell announced the construction of a prototype filling station by 2001 and expected *commercially working stations until 2004*. Shell study for mobility in Germany saw improved ICE vehicles as the dominating propulsion system; natural gas and biodiesel shall have a niche function and FCVs a market share between 7-20% in 2020. [WSS 5/99]
Q3 1999	*Renault and PSA*, in co-operation with the French Atomic Energy Commission CEA, Air Liquide, de Nora, Total Dina and Valeo, started a four year project to prepare the *market introduction of FCVs by 2010*. [WSS 5/99]
11/1999	Ferdinand Panik, Head of the project group FCs at Daimler, predicted that alternative fuels will become relevant no later than 2020. Alternative vehicles could achieve a market share of 25% (optimistic estimation) by 2010. [WSS 6/99]
12/1999	Foundation of the "European Hydrogen Association" (EAH) to present H_2-technology internationally and to promote the foundation of further national H_2-associations. [WSS 5/99]
12/1999	The German VDA announced its conviction in methanol and hydrogen as future fuels, but confirmed the dominant role of Otto and diesel engines during the next decades. Natural gas is seen as a fuel in the transition phase. [WSS 6/99]
1999	Shell Hydrogen was set up to pursue and develop business opportunities related to H_2FCs. [http://www.lchr.org/a/37/78/fc_shell.html, 08.11.2015]

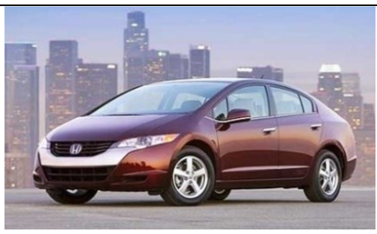
02/2000	Opel presented an LH_2-fuelled Zafira with ICE at the Geneva Autosalon, Erhard Schubert, Head of the German 'Global Alternative Propulsion Center' announced hydrogen as the fuel of the future. [WSS 2/00]
02/2000 05/2000 02/2005	BMW's CEO predicted that *BMW would sell several thousand H_2-propelled vehicles p.a. in 10 years*. [WSS 2/00]; BMW launched the first fifteen serial H_2-ICE vehicles (with FC APU). Burkhard Göschel, BMW Member of the Board for R&D, explained BMW's strategy not to rely on one or two-litre-vehicles, but on zero emission vehicles. He predicted a sufficient H_2-fuelling infrastructure in Europe by 2010. *Under the precondition of an adequate infrastructure he foresaw that every second person could drive an H_2-vehicle*. [WSS 3/00] BMW announced its transfer of the 7-series H_2-BMWs within the next 3 years to the customer. [WSS 1/05]
09/2000	At the HYFORUM in Munich Iceland's President Grimsson illuminated Iceland's plan to become the first H_2-economy by 2030 or 2040. *Toyota stated hydrogen as the ultimate fuel for FCs and planned a small FCV series for 2003* with the final decision on the fuel being made by 2000. [WSS 5/00]
10/2000	Foundation of "Fuel Cells Canada", a national industry association to promote FCs. [WSS 5/00]
10/2000	*William Ford stated that he believes in the ultimate dominance of the ICE*, but also announced a test fleet for the end of 2001. [WSS 5/00]
11/2000	VW presented the FC Bora HyMotion (75 kW FC, 50 litres LH_2-tank, 350 km mileage, maximum speed 145 km/h). [WSS 6/00]
Q4 2000	GM declared its abstention from the development of new FCV-models to concentrate on bringing a significant share of FCVs to market by 2010. [WSS 6/00]
11/2000	Daimler presented the Necar 5 in Berlin (methanol reforming). [WSS 6/00]
Q4 2000	Daimler and Mitsubishi joined in co-operation to develop FC systems for the Japanese market. [WSS 6/00]
01/2001	GM, Toyota and Exxon (reformer technology) joined to develop FCVs. [WSS 1/01]
01/2001	Publication of Road Map of the *Japanese* "Science and Technology Agency" for the market introduction of FCs in mobile and stationary applications by 2010: Phase I (until 2005): Technology development and prototype tests. Phase II: *Planned for a total commercialisation of FC technology by 2010*. A mobile FC for cars should cost 350 to 600 € in 2010; a stationary FC for home use shall cost between 800 and 1,150 €. [WSS 1/01]
02/2001	Presentation of the FC Ford Focus at the EC. Ford planned a test fleet of 50 FCVs in California by 2004 and announced a possible test extension to other locations and with more FCVs until approx. 2007 and start of sales to normal customers by around 2010. [WSS 1/01]
02/2001	During a roofing-ceremony of a demonstration in Essen, *RWE* CEO Dietmar Kuhnt, announced that RWE will invest a three-digit million sum in FC-technology by 2006 and that he expects that FCs will have a *share of 15% in electricity production by 2015*. [WSS 1/01]
Q1/2001 05/2003	Announcement of the CUTE and STEP project, see section 4.1.2. Within two years a small series of 30 FC buses shall be brought to market. [WSS 2/01] Inauguration of the first FC Citaro city bus in Madrid on 05.05.2003. [WSS 3/03]
02/2001	Shell started to market 12 W, 12 V FCs (US DCH technology) as replacement for batteries. H_2-storage systems (gas bottles, metal hydrides) are sold using the filling station network. [WSS 2/01]
03/2001	Rolf Zimmermann, Head of *Ford Germany*, announced that only *90% of the cars will have an ICE in 2010*. [WSS 2/01]
03/2001	Toyota manager Hiroyuki Watanabe announced that *Toyota* will present a new FC-prototype in 2003 and *will start serial FCV-production in 2010*. [WSS 2/01]
03/2001	Byron McCormick, Director of the GM R&D Centre, announced that GM, Toyota and VW jointly decided to use petrol for the market introduction of FCVs. A prototype shall be developed within the next year. McCormick declared that *GM wants to "be the first company to sell M1 FCEVs*". [WSS 2/01, p. 1; http://wardsauto.com/news-amp-analysis/gm-aims-be-1st-fuel-cell-mass-producer]

04/2001	VW CEO Piech announced that VW will develop FC-technology without using hydrogen directly. From his point of view, hydrogen is only suitable for buses or large fleets; in addition, it would be too dangerous to equip M40 cars/a with hydrogen. VW saw liquid fuels being ahead. [WSS 2/01]
05/2001	Scania presented a hydrogen propelled FC-bus with an efficiency of 52 to 57%, reducing conventional energy consumption by 60% at the London UITP conference. [WSS 3/01]
06/2001 03/2002	Toyota announced the transfer of the first H_2-vehicles (FC VH-4, CGH_2, maximum range 250 km, maximum speed 150 km/h, price 90 k€) to clients in 2003. [WSS 4/01] Toyota announced offering an H_2-car to its customers in the Tokyo area (range 250 km, price 75 k€) in 2003. [WSS 2/02]
06/2001	Quantum Technologies presented a 70 MPa H_2-tank containing 80% more H_2 than a comparable 35 MPa tank. [WSS 4/01]
07/2001	The Japanese Ministry for Economy, Trade and Industry announced its target of having *k50 FCVs on Japanese roads by 2010*. To reach that goal a 33 M€ project of GM, Toyota, Nissan, Honda and Daimler was announced. [WSS 4/01]
07/2001	On the occasion of the first anniversary of the “FC Network” in North-Rhine-Westphalia, Professor Stolten of FZ Jülich predicted that the FC has the potential to significantly change the energy world. First technically useful applications may be expected in three to four years, a market penetration could be expected within the next decade. [WSS 4/01]
07/2001	Manfred Remmel, CEO of RWE, expected the serial production readiness of stationary FCs for household applications for 2005, FCs capable of competing for 2007. [WSS 4/01]
10/2001	GM joined in partnership with the Canadian FC producer Hydrogenics. [WSS 5/01]
11/2001	The partners of the German VES agreed on hydrogen as the fuel with the largest future potential. Honda and Ford announced they would concentrate on the development of H_2FCs. *VW saw H_2 as an alternative to petrol and diesel at the earliest in 15 to 20 years*. GM still followed reforming plans. [WSS 6/01]
12/2001	Toyota founded a Hydrogen Research Centre. [WSS 1/02]
01/2002	BMW planned to offer its H_2-ICE BMW7 to customers before 2010. *If the infrastructure will develop accordingly, it has been planned to sell about 25% H_2-vehicles by 2020*. [WSS 1/02]
01/2002	The US government launched the “Freedom Car” research initiative “focused on collaborative, pre-competitive, high-risk research to develop the component technologies necessary to provide a full range of affordable cars and light trucks that will free the nation’s personal transportation system from petroleum dependence and from harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicles.” [http://www.afdc.energy.gov/pdfs/freedomcar_plan.pdf, 27.11.2011]
03/2002	RWE founded “RWE Fuel Cells GmbH”. [WSS 2/02]
03/2002	The German law for the promotion of CHPs supports stationary FCs with the payment of a bonus of 5.11 ct/kWh for a period of ten years after commissioning of the plant (the plant has to be commissioned by 31.12.2016). [Gesetz für die Erhaltung, die Modernisierung und den Ausbau der Kraft-Wärme-Kopplung of 19.03.2002, last change 25.10.2008, §7; VII]
04/2002 07/2002	*Honda* announced it would *start serial production of the FCX-V4 in 2003*. The car received official approval and homologation for road services in Japan. [WSS 2/02] The first FC vehicle, the Honda FCX, received Californian and US registration as a ZEV for use in public. [WSS 4/02]
05/2002	BVG and TotalFinaElf agreed an R&D co-operation on hydrogen.
06/2002	Foundation of the CEP by Aral, BMW, BVG, DaimlerChrysler, Ford, GHW, Linde, MAN, Opel and the German Ministries for Transport, Environment and Economy.
07/2002	Inauguration of an FC bus demonstration project, including the production of H_2 as a residue from a sewage plant, in Barth, Mecklenburg-Vorpommern. [WSS 4/02]
Q3 2002	The VDV (Association of transport companies) evaluated hydrogen as being the future fuel; emission-reduced diesel engines are seen as today’s propulsion system, natural gas engines do not play any role. [WSS 4/02]

Q3 2002	Storage technologies make significant progress: Dynetek tested an 82.5 MPa tank for use in vehicles at 70 MPa; Quantum reached US and EU registration for a 70 MPa system, increasing the mileage to 500 km. [WSS 4/02]
07/2002	The Japanese government installed two hydrogen demonstration projects (stationary and mobile). Honda, Toyota, Nissan, GM and DaimlerChrysler are participating in the mobile testing, using five filling stations in various parts of the country. [WSS 4/02]
07/2002	Inauguration of GM test FC R&D Centre in Honeoye Falls, USA. GM R&D Vice-president *Larry Burns confirmed GM's target to become the first car manufacturer to deliver M1FCVs; by 2010* a "significant" number of FCVs shall be delivered to the customer. [WSS 4/02]
08/2002	Laying of the cornerstone for the "Hydrogen Competence Centre" for R&D on fuel/electrolysis cells and its core components in Schwerin, Mecklenburg Vorpommern. Inauguration in 06/2004. [WSS 4/02, WSS 3/04]
09/2002	Ford presented the Ford Focus FCEV Hybrid which is built in a "mini serial" of 40 vehicles. *Ford planned the start of the marketing of FCVs for 2010*. [http://www.diebrennstoffzelle.de/-nachrichten/DerneueFordFocusBrennstoffzelleHybrid-TechnologiefrexzellenteFahrleistungen.shtml, WSS 5/02, p. 2]
Q3 2002	Test of the first FC locomotive: hauling engine, metal hydride storage tank for 3 kg H_2, 14 kW, permanent operation, traction sufficient for three times four tonnes wagons. [WSS 4/02]
2003	WE-NET (World Energy Network: International cooperation in research and development of clean energy system with particular emphasis on hydrogen) programme Japan, Osaka, 1993-2003: Introduction of a global network for the development of abundantly available renewable resources. Phase I (1993-1998): long-term concept in H_2-utilisation to develop core technologies indispensable to construct an H_2-network following supply and demand. Phase II (1999-2002): concepts on promotion and realisation of H_2-energy into society. In 2003, it was succeeded by the "Development of Fundamental Technologies in the Safe Utilization of Hydrogen" project as part of the "Hydrogen Energy Application Program in PEMFC". In 2002, 3 H_2-refuelling stations were built for the verification and evaluation of performance of continuous, safe operation and confirmation of parameter variation over time. Guidelines for safety and design were prepared, which led to standard specifications for H_2-refuelling stations. [http://www.enaa.or.jp/WE-NET/newinfo/station_taka_e.html, 19.05.2011]
02/2003	*VW CEO Bernd Pischetsrieder* announced that he did not see the advantage of FCs over the current petrol engine and that *he prefers synthetic fuels* which do not need exhaust gas treatment with a catalyst or diesel filter. [WSS 2/03]
03/2003	Daimler inaugurated its first Japanese test centre within the framework of the "Japan Hydrogen & Fuel Cell Demonstration Project" (JHFC) in Tokyo. In the Tokyo area five H_2-filling stations are located. [WSS 2/03]
03/2003	The Massachusetts Institute of Technology concluded that future (30-50a) transport systems with strongly reduced CO_2-emissions could be realised only when using hydrogen, even if it is produced from fossil fuels. [WSS 2/03]
Q1 2003	First test of a 70 MPa H_2-storage system in a GM vehicle increasing the vehicle range by 60-70% compared to a 35 MPa system. The fuelling time was less than five minutes. The worldwide first 70 MPA H_2-filling station (10 m³ LH_2-storage tank, maximum flow of 40 m³ H_2/min) was inaugurated at the Opel test centre in Dudenhofen. The station used a new compression procedure with 30 MPa high pressure storage buffer banks. GM and BMW announced a co-operation in the development of 70 MPa H_2-storage technology. [WSS 2/03]
Q1 2003	Start of the Hydrogen 700 project of DaimlerChrysler, Ford, Hyundai, Nissan, PSA Peugeot-Citroën and Toyota co-ordinated by Powertech Labs aiming to develop 70 MPa H_2-storage technology and to promote standardisation (ISO TC 197, EIHP). [WSS 1/03]
05/2003	BMW Executive Manager for R&D announced an efficiency target for the H_2-ICE of 50%. [WSS 3/03]
06/2003	US and EU signed a co-operation agreement on H_2&FC technology. [WSS 3/03]
06/2003	Klaudia Martini, Executive Manager of Adam Opel announced that GM and Opel invested 1 G€ in the development of FCs, preparing the technology for large serial production in 2010. GM started tests with the HydroGen3 on public roads. [WSS 4/03]

10/2003	*GM* Head of Department for Advanced Technology Strategies Christine Sloan confirmed the target of *starting serial production of H_2-vehicles by 2010 and having one million vehicles on the road by 2020*. [WSS 6/03]
11/2003	Foundation of the "International Partnership for the Hydrogen Economy" (IHEP) in Washington. [WSS 6/03]
Q4/2003	Honda developed a stack which is frost-proof up to –20°C. [WSS 5/03]
Q4/2003	The EC announced spending of 2.8 G€ on H_2-research projects between 2005 and 2015 [WSS 6/03]
01/2004	AirLiquide purchased Messer Griesheim. [WSS 1/04]
01/2004	The California Environmental Protection Agency reported a plan to install an H_2-filling station every 20 miles on Californian highways. This would need 200 filling stations, à 300 – 500 kUSD per station. 28 filling stations existed or were planned for. [WSS 1/04]
02/2004	AirProducts presented the "mini-fueller 100" at the German Wasserstoffenergie Tag in Essen. It is a compact fuelling system (1.2 x 1 x 2.3 m) to fill two to five vehicles per day which could use hydrogen from various sources. [WSS 1/04]
03/2004	The first "Parlamentarischer Abend", a meeting between Members of the Federal State Parliament and FC- and H_2-technology experts, took place in Berlin. [WSS 2/04]
03/2004	Foundation of the "Landesinitiative Brennstoffzelle" of the Federal State Niedersachsen in co-operation with VW. [WSS 2/04]
04/2004	Inauguration of the first H_2-ICE MAN bus in Berlin. [WSS 3/04]
05/2004	At the Hannover fair several FC-applications ready for market were exhibited, e.g. 1.2 kW H_2-fuelled FC-generator by Ballard; APU of the Duisburg FC Technology Centre etc. In general, Small FC applications entered early market phase. [WSS 2/04]
06/2004	Foundation of the Polish H_2FC Association in Cracow. [WSS 3/04]
06/2004	DaimlerChrysler handed over the first four A-class FCVs to Deutsche Telekom for testing in daily use. By the end of 2004, 60 cars shall be in the hands of the customer. [WSS 3/04]
Q22004	The EC finalised the first H_2FC-technology contracts within the Sixth Framework Programme, e.g. StorHy and HySafe. [WSS 2/04]
Q22004	The United Nations Development Organisation (UNIDO) founded an International Centre for Hydrogen Technology (ICHET) in Istanbul aimed at demonstrating viable technologies for the implementation of an H_2-economy as well as facilitating their widespread use, more particularly in developing countries. [WSS 2/04] It was closed down in 2012.
12/2004	Inauguration of the second H_2-filling station (Aral) in Berlin, Messedamm. [WSS 6/04]
Q4 2004	Jeremy Bentham, Manager Shell Hydrogen, predicted that H_2-vehicles will enter the mass market by 2015: M5-10 vehicles could be available by 2020 / M50 by 2030. GM Vice president Larry Burns announced H_2-cars being competitive with petrol cars in 2020. [WSS 6/04]
02/2005	During the "Internationaler Wasserstoff Tag" in Berlin Linde presented its study for the introduction of a hydrogen infrastructure in Germany. [WSS 1/05]
03/2005 06/2005	Prof. Dr. Kohler, Director of the Daimler Vehicle Research, announced that Daimler intends to start selling FCVs to general customers by 2012. [WSS 2/05] Prof. Dr. Kohler, Director of the Daimler Vehicle Research announced Daimler's intention to sell k100 FCVs by 2015; serial-production readiness should be achieved by 2012-2015. The target customers shall be corporate customers such as large logistic companies. [WSS 2/05]
03/2005	More than 500 FC- plus H_2-ICE vehicles are in existence worldwide; 70 MPa filling technology starts to take hold. [WSS 3/05]
08/2005	Sulzer Hexis stopped investment in the development of FC domestic heating systems. Since 2006, Hexis AG has continued its FC-activities in the legal form of a foundation. [WSS 5/05, WSS 1/06, http://www.hexis.com; 06.09.2009]
09/2005	The camper producer Hymer started to equip its S- and B-class campers 'on demand' with an FC "SFC 1600" (65 W) for a premium of 3 k€ to be filled with 10 litre methanol cartridges. A five litre cartridge costs about 20 Euro. [WSS 4/05]

2005	The H_2-R&D programme of the EU had a volume of 275 M€ for the period 2002-2006. In comparison, Japan spent 260 M€ and the US 235 M€ only in 2005. [WSS 4/05]
01/2006	Peugeot opened an FC Research Centre in the Paris region. [WSS 1/06]
03/2006	The German Minister for Transport, Wolfgang Tiefensee, announced a 500 M€ programme to support H_2FC-technology between 2007 and 2016. He stated that it would be possible to enter the mass market for cars by 2020. [WSS 2/06]
05/2006	Total agreed with BMW to implement three H_2-filling stations in Europe to promote the market introduction of H_2-vehicles. [WSS 3/06]
06/2006	Handover of two out of fourteen H_2-ICE buses in Berlin. [WSS 3/06]
07/2006	Hyundai announced that hybrid cars have no chance against FC-cars. Thus, Hyundai planned to quit hybrid technology and concentrate on FCVs. According to principal research engineer B. K. Ahn, FCVs will command a 90% share of the world's new vehicle market by the middle of this century. Hybrid technology is evaluated to be futureless because it still uses petrol. The efficiency for the well-to-wheel chain is just 16% for petrol cars, 20% for diesel and 26% for hybrids. Hyundai achieved 36% efficiency in the eight years it worked in FCV R&D; the goal is to achieve 42%. Hyundai forecasted an FCV-market share of 58% with M50 vehicle sales by 2025 and of 90% with M80 sales by 2040. [WSS 4/06]
10/2006	VW announced large progress in FC-development. The use of a new membrane allows the reduction of the operational temperature from 120°C to just 80°C. By 2020 VW could enter the market with an affordable FCV suited to daily use. [WSS 6/06]
11/2006	Agip opened an H_2-filling station at the Höchst industrial park. The H_2 is a residue product of the chlorine production and is transported via a 1.7 km pipeline to the filling station where it is compressed to 35 or 70 MPa using a new compression technology by Linde. [WSS 6/06]
04/2007	Industrial prognosis of the FC-market is 1 G€ for 2010 and about 20 G€ for 2020. [WSS 2/07]
05/2007	Expansion of the Duisburg FC Technology Centre with a new test and assembly centre. [WSS 3/07]
05/2007	GM's Chevrolet Sequel became the first FCV to achieve 300 miles (482 km) on one H_2-tank fill on public roads. The Sequel integrates an H_2-FC propulsion system with steer-and-brake-by-wire controls, wheel hub motors, Li-ion batteries and a lightweight aluminium structure. Three carbon composite 70 MPa H_2-tanks store 8 kg H_2. [http://www.greencar-congress.com/2007/05/chevy_sequel_dr.html; 15.09.2009]
11/2007	GM Vice President Larry Burns affirmed GMs plans to distribute hundreds of FCVs via retailers to the customers. Starting in 2012, large numbers of FCVs shall be produced. 100 Chevy Equinox FC SUV were successfully rolled-out to customers in 2008. [WSS 6/07; http://www.hydrogencars-now.com/chevy-equinox-fuel-cell-suv.htm; 19.09.2009] 
11/2007	 VW presented the "space up!Blue", an H_2PHEV able to travel 100 km on battery power alone (12 Li-ion batteries, 150 W_{el} solar panel atop the car to recharge the batteries, high-temperature (up to 160°C) FC, rear mounted electric motor (45 kW, 120 Nm), 3.3 kg H_2-tank, total range of over 350 km). [WSS 6/07, http://www.hydrogencarsnow.com/vw-space-up-blue.htm; 19.09.2009]
01/2008	2005-2007: Commercialisation of several FC-products in the luxury end, e.g.75% growth in new units delivered (some k12 units shipped in 2007); low temperature electrolyte DMFCs and PEMs made over 98% of the manufacturing. The 2007 global FC manufacturing capability was estimated at around k100 units p.a., with 25% from companies which exclusively develop H_2FC-technologies. The industry expects price reductions as manufacturing costs fall and subsidies become available. RD&D government funding topped 1 GUSD during 2007 with seven countries making up 0.8 GUSD. The cost of PEM products varied from 3 kUSD/kW for a 5 kW up to 34 kUSD/kW for a micro 100 W FC-uni. Annual cost reductions of 10-20% were reported. [http://www.fuelcelltoday.com/online/news/articles/2008-01/Fuel-Cell-Commercialisation; 17.10.2009]

01/2008	HyWays predicted that H_2-vehicles will become competitive between 2025 and 2035. Under the right circumstances the transport oil consumption could decline by 40% until 2050. This number is based on the assumption that M16 H_2-vehicles are operating and 16 G€ were invested in the infrastructure by 2030. [WSS 1/08]
03/2008	MB CEO Dieter Zetsche confirmed the start of the serial production of the FC-B-class in 2010, but on a low level. By 2014/2015 it is foreseen to increase the production numbers to k100 p.a. The B-class completed test runs under winter conditions in Norway. Cold-start of the FC at temperatures down to –25°C became functional. [WSS 1/08]
05/2008	Linde presented its first H_2-ICE forklift at the CeMAT in Hanover. [WSS 3/08]
05/2008	Toyota provided FC units for a Japanese stationary FC programme. [WSS 3/08]
05/2008	The CUTE project's 36 Daimler FC buses jointly reached a mileage of 2 Mkm. [WSS 3/08]
06/2008	BMW - in a consortium of 34 automanufacturers, aerospace, fuel companies and universities - developed a composite modular LH_2-storage system that can be formed into different shapes allowing greater packaging flexibility. [WSS 3/08]
06/2008	Munich-based start-up P21 which offers telecommunication solutions in remote areas completed a successful test of six kW FCs working as Uninterrupted Power Supply (UPS) systems in mobile telephone applications in the State of Kuwait. The system proved its reliability under outdoor temperatures of 55°C, a humidity of 10% and very dusty conditions. [WSS 3/08]Following bankruptcy of P21 it was taken over by Heliocentris, Berlin in 2011. Heliocentris also acquired FutureE, the German market leader for FC-telecommunications applications in 2014.
06/2008	Rapido SAS, one of the world's largest manufacturers of campervans, announced the serial integration of EFOY FCs in its 2009 programme. [WSS 4/08]
06/2008	Presentation of the GermanHy project on the origin of the H_2. The study stated that 20% of the transport energy demand will be covered by H_2 by 2050, see section 4.1.3
06/2008	 Production start of the Honda FCX Clarity, the first Honda which was originally designed as an FCV. Mileage was increased by 30% to 450 km, consumption was decreased by 25% to 3.2 petrol_{eq}/100 km, power density of the stack was increased by 50%, size of Li-Ion battery decreased 40%, its weight by 50%. The first vehicles were leased in the US. In the first three years 200 vehicles shall be leased out. [WSS 4/08, http://www.hydrogencarsnow.com/honda-fcx-clarity.htm; 20.09.2009]
07/2008	H_2-storage pressure upgrade to 70 MPa increased the mileage of the Daimler FC A-class from 160 to 270 km. F-CELL B-class is announced with a mileage of 400 km, FC stack size 40% smaller, 30% more performance, 16% less consumption (2.9 $l_{\text{diesel equiv}}$), good cold start characteristics, 100 kW, 320 Nm electrical motor. [WSS 4/08]
07/2008	Publication of the Roadmap of the California Fuel Cell Partnership "Vision for Rollout of Fuel Cell Vehicles and Hydrogen Fuel Stations": By 2010: hundreds of cars, about 10 FC buses and first regular filling stations. 2010-2013: Pre-commercial introduction of thousands of cars, dozens of buses and filling stations. 2013-2016: Early-market introduction of tens of thousands of cars, hundreds of buses and filling stations. [WSS 4/08]
09/2008	70 MPa extension of the Total H_2-filling station on Heerstraße in Berlin. Ultra low cold fill Linde technology pre-cools the H_2 allowing to fill 5 kg H_2 in 3 min. [WSS 5/08]
09/2008	Start of the Callux demonstration project (M75 € budget). By 2012 the aim is to install 800 stationary FCs at pioneering clients. Partners are: BAXI INNOTECH, Hexis/Vaillant, EnBW, E.ON, EWE, MVV Energie, VNG Verbundnetz Gas. 350 heating appliances were installed by the end of 2013, with M2.3 operational hours (256 a). [WSS 5/08, http://www.-callux.net/newsletter/11; 10.01.2014]
09/2008	The Scandinavian Hydrogen Highway Partnership of the three national Scandinavian networking bodies HyNor (Norway), Hydrogen Link (Denmark) and Hydrogen Sweden is targeted to provide a Scandinavian network of H_2-refuelling stations. [Scandinavian Hydrogen Highway Partnership, 2008, p. 1-4]
10/2008	SFC Smart Fuel Cell succeeded to sell 10,000 EFOY FCs. [WSS 5/08]

11/2008	 GM rolled out 100 HydroGen4 (440-cell stack, 73 kW electric motor, 3 carbon fibreH_2-tanks, vehicle range of 320 km, top speed of 160 km/h, temperature operating range: -25 to 45°C). In the CEP new customers are testing several vans as central part of the European FC test programme. The HydroGen4 is based upon the Opel Zafira like the HydroGen3. [WSS 1/09; 10.01.2014, http://www.hydrogencarsnow.com/gm-hydrogen3-minivan.htm; 03.10.2009]
01/2009	Daimler CEO Dieter Zetsche announced the start of FCV serial production for summer 2009. He expressed conviction that Daimler *could manage to reduce FC-costs to the range of a Bluetec-Hybrid (assuming production of k100 vehicles p.a.) within four to five years*. Daimler agreed with a German partner to install a German network of 1,000 filling stations at costs of 1.7 G€ (providing a maximum distance of 35 km for the customer to the next filling station). Zetsche demanded reliable standards to protect (R&D) investments. He declared that the beginning of the end of the oil area has already started. He believes it is wrong to count solely on electrical drives, but asked for the electrification of diesel and petrol drive trains. [Ostmann, Bernd: http://www.auto-motor-und-sport.de/eco/daimler-produktion-der-brennstoffzelle-beginnt-schon-im-sommer-953613.html; 25.07.2009]
01/2009	Publication of the EC Regulation 79/2009 on type-approval of hydrogen-powered motor vehicles and amending Directive 2007/46/EC.
02/2009	Foundation of HySafe, a co-operation of 20 research and industrial partners to work jointly on H_2-safety. The association operates a database on H_2-accidents. [WSS 2/09]
02/2009	Daimler estimated the implementation costs of a 1,000 H_2- filling station infrastructure at 1.5-2 G€ and that this investment would be feasible until 2017. [WSS 2/09]
03/2009	Dr. Ulrich Hackenberg, Executive Director at VW responsible for R&D, predicted that the future market for motorised individual mobility will be split between the industrialised and the newly industrialising countries. Growing markets such as China and India are, despite the financial crisis, on the way to a mass motorisation in the medium and long-term. In the classical industrialised countries, in particular in the mega-cities, it will be important to offer sustainable vehicle and mobility concepts, which - at arguable costs- will offer flexibility and a minimum burden to the environment. [Meiners, 2009, p. 21]
03/2009	BMW, Hoerbiger, TU Graz and HyCentA developed a monovalent H_2ICE with a efficiency of 42% for cars combining features of the Otto and the diesel engine with surface ignition followed by a diffusion combustion. A high pressure injection of H_2 to the combustion chamber with a pressure of up to 30 MPa allows the usage of the whole engine operating map. [Technische Universität Graz: BMW Wasserstoffmotor erreicht Spitzenwirkungsgrad In: MaterialNews, 13.03.2009; http://www.materialsgate.de/mnews/4131/BMW+Wasserstoffmotor+erreicht+-Spitzenwirkungsgrad.html?start=500, 04.10.2009]
03/2009	Laying of the cornerstone for the Blue Tower in Herten. In a multiple process of staged reforming, a clean, CO_2-neutral product gas, called Blue Gas, is produced from regenerative feedstock, such as roadside green cuttings, chicken manure and olive stones. Blue Gas can be used to produce electricity and hydrogen. The facility produces 150 $m^3 H_2/h$ which is provided to the neighboured H_2-competence centre Herten. [WSS 3/09]
03/2009	Baxi Innotech presented GAMMA 1.0, a stationary 1.0 kW FC heating device. [WSS 3/09]
04/2009	VW ordered 200 FC, Type EFOY 1600, at Smart Fuel Cell for installation to vans which are operated as mobile offices by various administrations. [WSS 07/09]
04/2009	Daimler announced the successor to the FC-A-class by the end of 2009. It shall be fully qualified for use by normal customers. Peter Froeschle, head of market development department stated that Daimler sees electricity and H_2FCs as the main infrastructure pillars for transport, storage and distribution of regenerative primary energy. [Hzwei (Editor).: „DWV erstellt Forderungskatalog. In: Hzwei – Das Magazin für Wasserstoff und Brennstoffzellen. Volume 9. Oberkrämer 2009, p. 4]

04/2009 2011 2013	The Japanese company Eneos CellTech built a plant for mass-producing FC home co-generation systems at the Gunma Factory site of Sanyo Electric (planned capacity of k10 units p.a. by 2010 and up to k40 units p.a. by 2015). The company estimated that it will be able to produce about k150 units from 2009 to 2015. [http://www.fuelcelltoday.com/online/-news/articles/2009-04/Eneos-CellTech-Opens-New-Plant-f, 12.02.2010] Eneos, Toshiba and Panasonic jointly produce household FC-appliances under the brand Enefarm. By **2011/ 2013** a cumulated number of k22/k50 units were installed. [http://www.fuelcellinsider.org/wp-content/uploads/2012/04/ENE-Farm-summary.pdf; 10.01.2014] Tokoy Gas and Panasonic announced to develop an EneFarm system also suitable for condominiums. In major Japanese cities, 'condos' account for roughly two-thirds of new residential property. The Ene-Farm FC cogeneration system consists of FC, hot water storage and backup heater units. In 2013, the Japanese government approved EneFarm as an efficient energy-saving system, setting a target of accumulated installation of M1.4 units by 2020, rising to M5.3 units by 2030. Tokyo gas alone aims to install k300 units by 2020. Unit costs (200-750 W_e) of 22 kUSD. [Semiconportal. Emerging tech from Japan: FC power generation for condos, 21.10.2013; https://www.semiconportal.com/en/archive/new-product/device/131021-panasonic-tokyo-gas-fuel-cell.html; 10.01.2014]
04/2009	Air Products installed an H_2-fuelling station at the Defense Distribution Depot in Susquehanna, Pennsylvania powering an overall fleet of 40 H_2FC-forklifts being used in daily warehouse operations. Lead-acid battery forklifts are powered alongside. Data to compare costs and operational characteristics are collected and analysed to support the development and commercialisation of H_2FC-technologies. H_2-powered materials handling equipment can be completely refilled in minutes, only once or twice daily depending on use. Traditional battery-powered equipment must be placed temporarily out of operation for battery replacement and requires battery recharging approximately every 4-6 h. H_2FC-equipment provides consistent power during use and does not experience decreased performance like traditional Lead-acid battery units at low SOC. H_2&FC equipment avoids Lead-acid battery storage and disposal. In addition, Air Products installed indoor H_2-fuelling infrastructure to fill a fleet of over 200 FC lift trucks to operate at Central Grocers' new distribution centre in Joliet, Illinois. [AirProducts Press Release: Air Products' Hydrogen Fueling Technology Powering Forklifts at Defense Distribution. 01.04.2009]
04/2009	Laying of the cornerstone for the first hybrid power station by a consortium of Enertrag and Total in Prenzlau. Combination of 3 wind energy turbines with a capacity of 6 MW, biogas and H_2-production (500 kW electrolyser), H_2-storage and power/heat generation (biogas-H_2-mixture in a CHP or by a stationary H_2FC) allows demand management. Excess H_2 can be used for transport purposes. [http://www.enertrag.com/download/presse/pm_2009-04-20_hybrid-kraftwerk_090420.pdf; 20.09.2009]
05/2009	On 11 May 2009, the HyNor Partnership and StatoilHydro officially opened the Norwegian Hydrogen highway 'HyNor' (one of a total of seven H_2-stations anticipated) at StatoilHydro's new H_2-station at Økern in Oslo. The opening was accompanied by the start of the EVS Viking Rally. The rally's vehicle fleet of 14 H_2-vehicles, two plug PHEVs and 14 BEVs was the first to drive on the Norwegian hydrogen highway. [http://www.hynor.no/, 11.02.2010]
05/2009	Austrian Frauscher dockyards offers the first serial production FC boat, i.e. the Frauscher 600 Riviera HP boat (6 m long, 4 kW electric drive powered by a Fronius FC, maximum speed of 5 knots (9 km/h), use of 11 kWh H_2-cartridges, which may be changed within minutes). The energy content is sufficient to operate the boat for 4 hours at full power, doubling the conventional battery performance. [WSS04/09]
05/2009	k5-10 FCVs are planned to be in operation in Hamburg by 2015. [Unruh, Randolf: Ratzfatz auf Linie. In: lastauto omnibus 05/2009. p. 38]
05/2009	Empa and the Paul Scherrer Institut (PSI) developed, in co-operation with Bucher Schörling, Proton Motor, BRUSA Elektronik AG and Messer Switzerland, the first FC powered street sweeper. The standard 55 kW diesel engine was replaced by a 20 kW FC system, a Li-Polymer-battery, an electric drive and a 6.5 kg H_2-storage system. The vehicle has a length of 3.78 m, is 1.28 wide and has a permissible weight of 4.5 t. [Press release proton-motor of 20090715 on hy_muve project, 12.02.2010]

05/2009	 Presentation of a Triple Hybrid FCBus (12 m, 18 t permissible weight standard bus, 120 kW, 65 km/h maximum speed, 20 kg CGH_2 at 35 MPa, sufficient for about 250 km). It was developed by Skoda Electric (bus, electric drive system and system integration), Czech research institution UJV (project co-ordination), Nuclear Research Institute Rezc and Proton Motor, i.e. the supplier of the energy system (50 kW PEMFC-system, battery and ultra capacitors). The bus has been operating in the city of Prague since mid 2009. It received the "Zukunftspreis Alternative Antriebstechnologien 2010" (Award for alternative propulsion technologies of the future) of the IDWI Innovationsvereinigung der Deutschen Wirtschaft (Association for Innovations in the German Economy). [renewableenergyfocus.com: Proton and Skoda launch triple-hybrid fuel cell bus, 15.09.2013; http://www.renewableenergy-focus.com/view/1786/proton-and-skoda-launch-triplehybrid-fuel-cell-bus-/, 11.02.2010]
06/2009	At the UITP conference Mercedes presented the next generation of the Citaro FC hybrid bus (11.95 m, 35 kg CGH_2 storage at 35 MPa providing a range of 250 km, two FC-stacks with each 396 cells providing 60 kW power, 330 kg Li-Ion-battery with a capacity of 26 kW, two electric wheel hub motors with a power of each 80 kW). The average H_2-consumption of 10-14 kg/100 km was cut in half compared to the precursor model. The vehicle weight was reduced to 13.2 t, thus the city bus is allowed to carry 76 passengers (formerly 72). [Unruh, Randolf, 05/2009. p. 38; WSS 01/10, p.1]
06/2009	A HotModule FC CHP of MTU Onside Energy was installed at the Munich Erdinger Weißbräu brewery. The power is 240 kW_{el} and 200 kW_{th}. Biogas (85% CH_4) produced from in-house anaerobic waste water treatment is used as combustion gas for the FC. It is reformed at 650°C to hydrogen. About 50% of the energy content of the biogas is turned to electricity, about 40% to a 400°C hot rejected heat. The total efficiency of the plant is 90%, about 1.2 Gg CO_2 are saved p.a. by the operation of the new plant. [WSS 04/09]
07/2009	Smart Fuel Cell AG presented the new EFOY 2200 delivering 90 W at the Düsseldorf Caravan salon. It packs 38% more power than the EFOY 1600 and recharges the board battery with a maximum of 2.2 kWh/d. It can be ordered from the Internet from ordinary resellers at a price of about 4.8 k€. [WSS 05/09, Yatego price information 12.02.2010]
08/2009	GM introduced the fifth generation of its FC (93 kW, same power as the precursor model, significant cost reduction, platinum demand reduced from 80 g to 30 g (10 g planned for next model), increased lifetime from 80-120 k-mi). GM is still optimistic about being able to present a model ready for serial production by 2012. [WSS 05/09]
09/2009	The high temperature FC (HotModule of MTU Onsite Energy, 320 kW, LNG-fuelled) started operation on the offshore supply vessel Viking Lady, within the FellowSHIP project. It is fully integrated into the on-board power generation infrastructure and avoids the emissions equal to almost k20 private cars. Project partners include Det Norske Veritas, Wärtsilä Norway and Eidesvik Offshore ASA, the Norwegian operator of the ship. MTU Onside Energy stopped FC-activities in 2010, all stored materials and equipment were transferred to Fuel Cell Energy Solutions GmbH, the German subsidiary of US Fuel Cell Energy. [http://www.-shipbuilding-industry.eu; 12.02.2010; http://www.hzweiinfo/blog/2012/07/18/revival-vom-hotmodule/; 10.01.2014]
09/2009	Linde, Daimler, EnBW, OMV, Shell, Total, Vattenfall and the German National Organisation for H_2FCs NOW signed a Memorandum of Understanding for the development of an H_2-infrastructure, i.e. "H_2 Mobility initiative". The MoU consists of two phases. Phase I (co-financed by the German Federal government and other programmes): Investigation of different options for a national H_2-fuelling-station-network and development of a joint, economic business concept taking into consideration public subsidy options. Phase 2: Extension of the fuelling station network, if the concept results are positive. [Umweltdialog (Editor): "H2 Mobility" - Aufbau einer Wasserstoffinfrastruktur in Deutschland: In: Umweltdialog, 22.09.2009]

09/2009	Linde officially inaugurated its second German H_2-liquefaction facility with a capacity of 3,000 l/h or 5 Mg/d cryogenic H_2 in Leuna. [GlassGlobalCommunity (Editor): Linde AG: Linde erects hydrogen liquefaction plant in Leuna. http://de.glassglobal.com/linde_gas_division/news-4662.html, 14.01.2014]
10/2009 2012	The Australian company Ceramic Fuel Cells Ltd. (CFC) opened a manufacturing plant (design capacity of k10 FC stacks p.a., investment of total 9.5 M€) in Oberbruch, North Rhine-Westphalia. In 2012, CFC started commercialisation of BlueGEN in Germany, UK and BeNeLux and selling the unit to commercial and end customers. BlueGEN (1.5 kW_{el}, 0.6 kW_{th}) is a natural gas-fuelled and FC-based, highly efficient micro plant designed to provide homes, public facilities and smaller companies with electricity and heat. [http://www.chemie.de/news/thema/ceramic-fuel-cells/; http://www.bluegen.de/uploads/tx_news/-120416_ChemCologne_Produktion_alit_ntsversprechen_Einzelseite_5.pdf; 14.01.2014]
10/2009	BC Transit, Vancouver, British Columbia received its first FC low-floor bus (Ballard FC, 450 km range, top speed of 90 km/h). A 20 H_2FC bus fleet (world's largest H_2FC bus fleet) was in operation in Whistler during the 2010 Olympic and Paralympics Winter Games and beyond. The project is part of the British Columbia's Hydrogen Highway, a voluntary network of Canadian technology providers, government partnerships and technology users who are working together to bring H_2FC-products to the marketplace. In 2013, the government of British Columbia announced it will not be continuing with the Whistler H_2FC-bus demonstration project when it expires in March 2014. The twenty buses will be replaced with diesel buses. The bus fleet drove 3.7 Mkm (more than 100 km/d), the availability was larger than 98%. [http://www.renewableenergyfocus.com/view/4386/canada-takes-delivery-of-first-hydrogen-fuel-cell-bus-for-olympic-fleet/; 16.10.2009, http://www.fuelcelltoday.com/news-events/-news-archive/2013/december/whistler-hydrogen-fuel-cell-bus-demonstration-project-to-be-discontinued; 10.01.2014]
10/2009	At the Tokyo Motor Show Honda's chief executive Takanobu Ito declared "over the long term, the advancement of electromotive technologies is an important factor for the reduction of CO_2-emissions. Among potential solutions, we believe that the FCEV will be the ultimate form for automobiles in the future as it has advantages such as zero CO_2 emissions in use, can travel considerable distances without refuelling and can be quickly refuelled." [http://www.hondanews.com/releases/41st-tokyo-motor-show-remarks-by-honda-motor-co-ltd-president-and-ceo-takanobu-ito?l=en-US&mode=print; 14.01.2014] Toyota confirmed its belief in FCs. By 2015 Toyota will market an FCV which will use much of the same technology of its hybrid models. [WSS 2/10]
12/2009	The US Government declared CO_2 a 'toxic' gas that endangers public health. This statement provides a legal basis for capping harmful emissions and will allow EPA to regulate GHGs from vehicles, power utilities and heavy industry even without legislation in Congress. EPA could begin to make rules as soon as 2010 under existing laws. [http://dailysignal.com/2009/12/07/epa-formally-declares-co2-a-dangerous-pollutant/, 13.02.2010]
01/2010 03/2014	Hamburg Hochbahn announced it would remove diesel buses from use by 2018; only FC-buses will be procured by then (about 60-70 buses p.a.). It is assumed that the operation of buses on fossil fuels will become cost inefficient by the early 2030's. Already in 2011, ten new FC-buses of the Citaro type will be purchased. [WSS 2/10] In reality, 4 new FC Citaro buses were put into operation in 2011/12. A total of 7 buses is planned. [http://www.sauber-bus.de/; 11.01.2014] In 07/2014 two battery buses with FC range extender were ordered at Solaris. Since 2014 four new FCH-Citaro buses are in operation in Stuttgart. Stack life has been prolonged to k12 operational hours, due to lower fuel consumption of 8-10 kgH_2/100 km (compared to formerly 22 kgH_2/100 km) only 7 instead of 9 H_2-containers are installed carrying 35 kgH_2. The efficiency has been improved from 38-43% to 51-58%. The Stuttgarter Straßenbahnen became a CEP-member in 12/2013. [WSS 1/14, WSS 3/14, 05/14]
02/2010 2011	Solvay, a chemical & pharmaceutical Group, ordered a 1 MW H_2PEMFC power plant for its Chlorine-alkali plant in Antwerp-Lillo (total value of 4.5 M€). H_2 is a by-product of the production process. It is NedStack's, Arnhem, largest order since its establishment in 1998. The plant was inaugurated in 2011 (efficiency of η_e = 50%, n_{total} = 80%). [nedstack company information: http://www.nedstack.com/applications/demonstration-systems, http://fuelcellsworks.com/-news/2010/02/11/largest-emission-free-power-plant-1-mw-pem-fc-power-plant/, 19.05.2012]

02/2010	Toyota presented its FCHV advanced ($FCHV_{adv}$, 90 kW Toyota PEMFC, 4 CGH_2 70 MPa fuel tanks (156 l), NiMH-battery, up to 690 km range (highway driving with 1 kgH_2/100 km)) which is based on its Highlander mid-size SUV. It utilises the core hybrid synergy drive (HSD) technology of the Toyota Prius. By 2012, more than 100 $FCHV_{adv}$ shall be deployed. [Toyota company information]
05/2010	The Federal State of North Rhine-Westphalia becomes a member of the CEP (first membership of a territorial state). [WSS 4/10]
06/2010	Daimler and EnBW jointly started the project "e-mobility Baden-Württemberg" to implement 200 BEVs or FCVs; mid-term: the whole EV-portfolio of Daimler). EnBW will provide the necessary infrastructure of 700 recharging points and three H_2-filling stations. It is co-financed by the "Landesinitiative Elektromobilität", a programme of the Federal State of Baden-Württemberg, budget of 28.5 M€ (2010-2014). Daimler CEO Zetsche announced that *FCV-costs will converge to diesel vehicle costs if an annual production of k100 vehicles is achieved*. [EnBW press information of 18.06.2010]
06/2010	The German Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW) published a study showing that the Lithium ressources are sufficient to cover the growing demand of the battery industry. [Schott, Benjamin, June 2010 p. 3-6]
07/2010	Green Corridor Project: The Brennerautobahn AG announced the production and distribution of 'green' hydrogen along the Brenner motorway (the construction of an H_2-filling station every 100 km along the section Munich–Modena is foreseen). In a first phase, Brennerautobahn considered investing in H_2-CH_4 blend vehicles, with ICE, awaiting for the circulation of FCVs. In 2011 Brennerautobahn AG presented a prototype truck operating on hydromethane (H_2-share about 30%) in Trient. The vehicle was developed in co-operation with "Centro Ricerche Fiat", Iveco and Fiat Powertrain. The H_2-filling station in Trient opened in 2013, the station in Bozen is under construction. [http://www.stol.it/index.php/Artikel/Chronik-im-Ueberblick/Lokal/-Brennerautobahn-setzt-auf-Wasserstoff-und-Methan; 11.01.2014] 
07/2010	Honda announced it would lease the Honda FCX Clarity to customers in California and Japan, for 600 USD/month for a three-year contract. Originally, 200 FCVs should have been leased out in California by 2013, but only 25 leasing contracts were realised. [Morey, Bruce: Fuel cells return to focus. In: SAE international, http://articles.sae.org/11975/, 11.012014]
07/2010	The US company Sprint Nextel equips the broadcast stations of its mobile telephone network with another 260 FC-stations (510 in total) instead of diesel generators for back-up against electrical power outage. [WSS 5/10]
07/2010	Announcement of the H_2MOVES project to implement FCVs in Scandinavia. Among other vehicles, two Fiat/Alfa Romeo MiTo equipped with a Nuvera FC, Li-ion battery and 70 MPa technology shall be implemented in Oslo. These two FCVs have never been implemented. SINTEF press information on "European-project-to-gain-customer-acceptance-for-electric-vehicles-with-fuel-cells-in-Scandinavia"; Accessed: 03.02.2014]
10/2010	Air Products plans world's longest H_2-pipeline. The new 290 km pipeline section will unite over 20 H_2-plants and 966 km of pipelines to supply the Louisiana and Texas refinery and petrochemical industries with over M28 m³ H_2/d. It is currently under construction (2014). [http://pipelinesinternational.com/news/new_hydrogen_pipeline_proposed_in_us/044347/#, http://www.airproducts.com/products/Gases/supply-options/pipeline.aspx; 11.01.2014]
10/2010	The start-up company SunHydro opened a commercial, public solar-powered 70 MPa H_2-station for cars and buses in suburban Connecticut as part of a future "Hydrogen Highway" stretching from Florida to Maine. H_2 is generated on-site using a combination of solar cells and hydrolysis technology developed by SunHydro's parent company, Proton Energy Systems. The deionised water is split at a semipermeable PEM. SunHydro is planning 9 stations along the US East Coast, e.g. portable stations (2.4 m x 12 m) which could fuel about 10 H_2-cars/d. Station costs will be between 100-200 kUSD. [Wiegler. Laurie: First Commercial Hydrogen Filling Station Opens. 20.10.2010, In: IEEE Spectrum, http://spectrum.-ieee.org/transportation/advanced-cars/first-commercial-hydrogen-filling-station-opens, 06.04.2012]

10/2010	The US Fuel Cell Council (USFCC) and National Hydrogen Organisation (NHA) consolidated to jointly promote the market introduction of H_2-energy and FCs. [WSS 1/11]
10/2010	BMW implemented 100 FC forklifts and trucks delivering process parts to assembly machines throughout its site in Spartanburg, South Carolina. The Lead acid batteries are replaced with H_2-FCs supplied by New York company Plug Power Inc. The H_2-fueling system consists of a ionic compressor, including six indoor dispenser stations supplied by Linde North America. The H_2 is a by-product of a sodium chlorate plant, which Linde purifies, compresses and liquefies using electricity produced from renewable hydropower. The refueling of the vehicles takes less than three minutes, compared to 15-20 minutes needed to change a battery. The fleet was extended by another 175 FC-forklifts in 2013. [https://www.bmwusfactory.com/bmw_articles/bmw-manufacturing-introduces-hydrogen-fuel-cell-material-handling-equipment/; 11.01.2014]
11/2010 09/2014	Delphi developed a 5 kW SOFC APU that directly generates electric power for commercial vehicles from natural gas, diesel or bio-diesel with low noise level. The APU may power in-cab electrical accessories or belt-driven components such as engine cooling fans and water pumps of HDVs. Currently, these features are powered by idling of the main engines or with diesel engine APUs. Thus, it will remove loads from the primary engine, resulting in improved vehicle fuel economy and engine performance. The SOFC APU can be incorporated into the architecture of a commercial vehicle by the manufacturer with minimal modifications. [http://ppd.delphi.com/pdf/ppd/cv/energy/solid-oxide-fuel-cell-auxiliary-power-unit.pdf, 23.05.2011] In 2011, BMW and Delphi presented the first vehicle equipped with a SOFC APU using petrol. The efficiency of the SOFC is 100% higher than the conventional system of engine, generator and battery. [Schätzl, Andreas: Spritsparen mit Zukunft. 17.05.2010 In: http://www.sueddeutsche.de/auto/bmw-mit-neuer-brennstoffzelle-spritsparen-mit-zukunft-1.555090] BMW announced to present a H_2FCPEM (International Fuel Cells, a daughter company of UTC) in its BMW 7 at the Clean Energy Expo in 2015 and to offer it afterwards for the general market. [http://www.ingenieur.de/Fachbereiche/Antriebstechnik/BMW-ruestet-erstes-Serienauto-Welt-mit-Brennstoffzellen-Batterie]
11/2010	The German organisation on gas and water supply, the Deutscher Verein des Gas- und Wasserfaches – DVGW investigated the feeding, storage and transport of H_2 and biogas through the natural gas grid. The German natural gas network has a length of 0.4 Mkm and an undersurfarce storage capacity of 20 Gm³ (to be extended to 30 Gm³ by 2020). In total 10^{12} kWh gas are transported annually. [http://www.dvgw.de, 23.05.2011]
12/2010	Daimler transferred the first B-F-Cell vehicles (100 kW, 290 Nm, 3.3 $l_{diesel\ eq.}$/100 km according to NEDC, cold start up to –25°C,) to customers (German Federal and National adminstrations). It is planned to put another 70 vehicles in Califonia to daily-use in 2012. In spring 2011, Daimler delivered its first B-cell FCVs to customers in the US. The technology shall be ready for serial production by 2015. The new FC-system of the B-class generation is 40% smaller and has a 30% higher capacity than the earlier A-class. Daimler actively promoted FCV leasing on its homepage. In 2014, several hundred FC cars are on the road in California, but no list of manufacturers is available. [WS 1/11; http://cafcp.org/faq/how-many-are-road; http://cafcp.org/faq/fcev_faqs_0; 11.01.2014]
01/2011	The “Karlsruher Institut für Technologie” (KIT) and the Ulm University founded the “Helmholtz-Institut Ulm für Elektrochemische Energiespeicherung” (HIU Ulm for Electro-chemical Energy Storage). Associated partners are the “Zentrum für Sonnenenergie- und Wasserstoff-Forschung (ZSW)“ and the „Deutsche Zentrum für Luft- und Raumfahrt (DLR)“. The annual budget is 5 M€. [WSS 1/11]
01/2011 06/2011	After the FC world tour, Daimler CEO Dieter Zetsche announced it would start with the serial production of the B-cell by 2014. By then, the technical performance of the FCV is expected to be at least competitive with the ICE. The additional cost for the FC shall be about 3 k€, for the complete FCV about 30 k€; comparable to a diesel HEV. It is planned to integrate FC technology into C-, E-, and S-class. Daimler plans to erect a further 20 H_2-filling stations together with Linde by 2014. [WSS 2/11]

01/2011	Daimler announced postponement of the market entry of A and B-class BEVs (originally, it was planned to start selling BEVs by 2012) to at least 2014. Due to a change in strategy, the B-class shall be introduced as Range Extender (2013/2014) and FCVs (2015) and eventually as HEV. According to Daimler BEVs involve uncalculable risks, e.g. purchasing or leasing of the battery by the customer, lifetime and residual value of the battery, avaiability of subsidies, development of infrastructure. The A-cell BEV is at the market for for selected customers since 2012, the B-class BEV marketing is announced for 2014/2015. [http://www.handelsblatt.com/auto/nachrichten/mercedes-b-klasse-electric-drive-souveraene-fahrleistung/8907128.html; 12.01.2014]
01/2011 09/2012	Toyota, Honda, Nissan and ten other Japanese companies announced the introduction of serial FCVs for 2015. In the areas of Tokyo, Nagoya, Osaka and Fukuoka the erection of 100 H_2-filling stations is planned. [WSS 2/11] *Toyota announced serial production of FC Prius would start in 2014*. Toyota will offer FCEVs with a higher mileage, price *> 50 kUSD; current costs: about 100 k€, a 30-40% cost reduction is necessary for market introduction*. HEVs should support electric driving only up to 25 km. BEVs should be offered only in several years' time when better batteries become available. [Seiwert, Martin: Toyota setzt künftig auf die Brennstoffzelle. 29.09.2012, In: http://www.-wiwo.de/unternehmen/auto/autobauer-toyota-setzt-kuenftig-auf-die-brennstoffzelle/7196212.html]
Q1/2011	 Transport for London (TfL) ordered 8 FC-buses (Ballard FC 75 or 150 kW) from ISE and Wrightbus. TfL participates in the EU CHIC-project. The buses operate out of First's Lea Interchange bus depot at Stratford in east London, where a permanent H_2-refuelling station maintained by Air Products is located. [http://www.ballard.com/fuel-cell-applications/bus.aspx; 06.04.2012]
04/2011	IEA stated that peak-oil already happened in 2006. [WSS 4/11]
05/2011	Air Liquide and Honda joined the CEP. Air Liquide declared that hydrogen is a driving factor for the company's growth. Air Liquide has 40 years of H_2-experience along the whole value chain, incl. implementation of about 50 H_2-filling stations world-wide. The CEP planned to erect five 70 MPa H_2-stations in Düsseldorf, Hamburg (HafenCity and Bramfelder Chaussee) as well as in Berlin (Sachsendamm and Heidestraße) by 2012. Honda has been doing FC-R&D since the mid 1980s. During the last ten years Honda has delivered several FCEV to customers worldwide. Honda introduced the Honda FCX Clarity to the CEP, which has been in operation in Europe since September 2009. [H_2gate-News: Die Clean Energy Partnership wächst mit neuen Partnern Air Liquide und Honda. Email, 20.05.2011]
06/2011	Daimler and Linde announced construction of 20 H_2-filling stations in Germany within the next three years. The total investment will be 20 M€. The new filling infrastructure will be built up in Stuttgart, Berlin and Hamburg as well as along an integrated North-South and East-West connection. Today, 7 public filling stations exist in Germany. Large cities need five to ten filling stations for a customer-friendly covering of the area. [Mertens, Frank: Daimler und Linde bauen 20 Wasserstoff-Tankstellen. 01.06.2011. In: http://www.autogazette.de/unter-nehmen/Daimler-und-Linde-bauen-20-Wasserstoff-Tankstellen-321814.html, 28.06.2011]
07/2011	Pike research predicted k5.2 H_2-filling stations for 2020 covering an H_2-demand of 418 Gg, needing an investement of 8.4GUSD. [05/2011]
07/2011	Start of construction of RH_2-WKA, Neubrandenburg, a windpark with a capacity of 140 MW connected to a storage system consisting of an electrolyser (1 MW, 210 Nm^3H_2),storage at 31 MPa and a 250 kW_{el} CHP. It was opened in September 2013. [http://www.rh2-wka.de/]
09/2011	Greenpeace collected its first k3 customers for wind gas contracts (provision of H_2 through the natural gas network). In 2014, customers still receive natural gas due to lack of windgas. [06/2011 WSS; http://www.greenpeace-energy.de/windgas.html; 12.01.2014] Delivery from Enertrag has been announced in 2014.
09/2011	Opening of the first public H_2-filling station in the UK in Swindon. [06/2011]
10/2011	Opening of the Enertrag/Total hybrid power plant: 3 wind turbines produce electricity which is partly used to produce H_2. H_2 is stored and used in the biogas power plant on demand. [WS 06/2011]

11/2011	Ballard Power Systems Inc. established a sales office in Hürth – North Rhine-Westphalia, Germany to establish projects throughout Germany and Europe. [http://www.hyer.eu/-members/germany/north-rhine-westphalia/north-rhine-westphalia-news/ballard-branch-in-hurth-germany-as-a-gateway-to-europe; 27.07.2013]
12/2011	Foundation of the initiative "performing energy - Bündnis für Windwasserstoff (Alliance for wind hydrogen)" with 14 partners from industry, R&D and other organisations with support from the Federal States of Brandenburg, Schleswig-Holstein and Hamburg. It is aimed at demonstrating H_2-blending to the natural gas network, re-conversion into electricity and H_2-storage in salt caverns. [01/2012]
12/2011	BMW and GM planned co-operation on FC-technology, GM shall share technology and costs with BMW. [http://www.wiwo.de/unternehmen/industrie/brennstoffzelle-bmw-und-gm-wollen-kooperieren/5944494.html; Accessed: 27.07.2013]
01/2012	Foundation of UK H_2Mobility to support H_2FC market introduction by 13 industrial and more other partners. [WSS 02/2012]
03/2012	Fraunhofer-Institut für Solare Energiesysteme ISE installed solar 6 m^3H_2/h-electrolyser / 70 MPa filling station in Freiburg. [WSS 03/2012]
04/2012	VDMA (German Association of Manufacturing and Plant Engineering) expected a turnover of more than 1 GEuro with FC technologies by 2020. [WSS 03/2012]
05/2012	The use of an incorrect valve caused a fire at AC Transit's 10 MUSD new H_2-bus fueling station. The neighbourhood had to be evacuated. A pressure relief valve at the H_2-fuel plant was made with a type of hard steel known to crack and fail when exposed to hydrogen. [http://www.mercurynews.com/breaking-news/ci_21149277/wrong-valve-cause-fire-at-ac-transit-hydrogen; 26.07.2013]
06/2012	Daimler, Linde, Air Products, Air Liquide and Total agreed on the build-up of another 36 H_2-filling stations to install a 50 station network by 2015. The programme is co-financed by the NIP with 20 M€. [http://www.bmvi.de/SharedDocs/DE/Pressemitteilungen/2012/125-ramsauer-wasserstofftankstellen.html?linkToOverview=DE/Presse/Pressemitteilungen/pressemitteilungen_node.html%3Fgtp=36166_list%25253D1; 26.07.2013]
06/2012	Mercedes-Benz opened an FC production and technology development facility in Burnaby, Canada creating 50 jobs at a 3,300 m^2 section of a Ballard Power facility, investing 53 MUSD. Production of FC stacks shall start in 2013, with the stacks being shipped to Germany for use in sedans such as the Mercedes-Benz C-Class or E-Class. [http://www.bclocalnews.com/business/159920695.html; 26.07.2013]
06/2012	BMW terminated co-operation with GM on FC-technology. [http://www.wiwo.de/unter-nehmen/auto/kooperation-geplatzt-bmw-beendet-gespraeche-mit-gm-zum-projekt-brennstoffzellen/6808678.html, 28.06.2012]
06/2012	A station measured more than 400 ppm CO_2 in the atmospere in the Antarctica. [WSS 04/2012]
07/2012	JX Nippon Oil & Energy Corporation opened a test laboratory at ZBT Duisburg to investigate German circumstances, e.g. natural gas quality for introduction of stationary FCs (home appliances) to German market. [WSS 05/2012]
08/2012	AirProducts inaugurated H_2-filling station at Shell station in HH Barmbeck. [WSS 05/2012]
09/2012	Hyundai plans to sell k1 FCEV Tucson in Europe until 2015, production costs 44.7 kUSD. [http://www.reuters.com/article/2012/09/25/us-autoshow-paris-hyundai-fuelcell-idUSBRE88O-0XQ20120925; 12.01.2014]
09/2012	A UK study stated that the European H_2FC-industry supports over k9 jobs (k3 directly and k6 indirectly) today. The global industry shall create about M0.7 direct jobs by 2020, of this M0.5 for stationary applications. Adding indirect jobs, e.g. for installations M1 jobs are expected. [UK Hydrogen and FC Industry: http://www.ukhfca.co.uk/wp-content/uploads/Hydrogen-and-Fuel-Cells-benefits.pdf]
09/2012	Toyota, Nissan, Honda and Hyundai signed an MoU with various organisations from the Nordic Countries on market introduction of FCEVs and H_2-refuelling infrastructure between 2014-2017. [http://www.scandinavianhydrogen.org/shhp/press/toyota-nissan-honda-hyundai-sign-mou-on-market-introduction-of-fuel-cell-vehicles-in-nord; 26.07.2013]

10/2012	ZSW inaugurated a 250 kW pressurised alkaline electrolyser to produce CH_4&H_2 from green electricity. It can produce up to 300 Nm³ H_2/d. [ZSW-Press-Release: http://www.zsw-bw.de/infoportal/presseinformationen/presse-detail/weltweit-groesste-power-to-gas-anlage-zur-methan-erzeugung-geht-in-betrieb.html]
11/2012	Plug-power received MUSD 2.5 from US DOE to convert electric tow tractor ground equipment to H_2FCs in airport applications in a 3-year project. 15 tractors will be deployed at FedEx's airport hub locations in Memphis, Tennessee and Oakland. [Plug-power Press Release of 20.11.2012 on "2.5 million DOE award will expedite fuel cell commercialization outside of material handling"]
11/2012	Nokia Siemens Networks is working with Ballard Power Systems to develop mobile networks that can continue to operate during power blackouts. A base station in FC-combination can provide 4.5 kW for approximately 40 hours on a single tank of fuel. Japanese operator NTT DOCOMO evaluated the system for potential commercial deployment. [Press Release: http://www.nokiasiemensnetworks.com/news-events/press-room/press-releases/nokia-siemens-networks-ballard-power-systems-develop-fuel-cell-backup-power-for-mobile-net, 10.02.2013]
11/2012	The Federal State of Brandenburg tested FCs for back-up of the new Federal Digital radio network, the project is funded by the NIP. [WSS 01/2013]
11/2012	The California Energy Commission issued a competitive grant solicitation to award up to 28.59 MUSD for new H_2-refueling stations in 25 selected areas to accommodate the planned large-scale roll-out of FCVs commencing in 2015. Individual projects are eligible for up to 65% of the total project cost or 1.5 MUSD, whichever is less. [http://www.greencarcongress.com/2012/11/cech2-20121120.html; 26.07.2013]
12/2012	Enertrag, Linde and Total laid the foundation stone to the first CO_2 neutral H_2-filling station at the Schönefeld airport. A wind park specially planned by Enertrag delivers the necessary electricity. The station is part of the CEP. [Total press release: http://www.total.de/ueber_total/news/pressemitteilungen/grundsteinlegung-schoenefeld.html; 10.02.2013]
01/2013	*BMW Group and Toyota Motor Corporation signed binding agreements aiming* at a long-term collaboration for the joint development of an FC stack and system, H_2-tank, motor and battery for completion in 2020. The companies are to collaborate also in developing codes and standards for the H_2-infrastructure. [BMW Press Release: https://www.press.bmwgroup.com/united-kingdom/pressDetail.html%3bjsessionid=LvSHRy0CTt3JLhy223GKFBN8gtJmHHThSJnC139Mszq20D8qz0Qb!-892092911?title=bmw-group-and-toyota-motor-corporation-deepen-collaboration-by-signing-binding-agreements&outputChannelId=8&id=T0136523EN_GB&left_menu_item=node__2201, 26.07.2013]
01/2013	The global H_2FC energy market is projected to be worth over 180 GUSD in 2050, revenues in the FC sector are projected to grow at a rate of 26% p.a. over the next decade, (revenues would octuplicate within the decade) according to a report of the Partnership for Advancing the Transition to Hydrogen. [HPATH Press release: http://www.hpath.org/PATH%20Annual%20Report%20Press%20Release_FINAL.pdf; 26.07.2013]
01/2013	*Daimler AG, Ford Motor Company and Nissan Motor Co. Ltd., signed an agreement* for the joint development of an FC-system to speed up development and significantly reduce investment costs: It is expected to launch world's first affordable, mass-market FCVs vehicles as early as 2017. [Ford Press Release: http://www.fordinsidenews.com/forums/archive/index.php/t-9668.html, 26.07.2013]
02/2013	Hyundai started the first serial production of ix35 FCEV. It is planned to produce k1 FCEV/a for lease in Europe by 2015. The ix35 has a 100 kW FC, 24 kWh Li-polymer battery, 588 km mileage, 0.96 kgH_2/100 km, max speed of 160 km/h. [http://news.xinhuanet.com/english/business/2013-02/26/c_132194002.htm; Seoul 26.02.2013]
03/2013	Ballard Power Systems signed an agreement with the Volkswagen Group for a 4-6 year Engineering Services contract to advance development of FCs for use in demonstration cars in VW's research programme. The contract value is around 60-100 MC$. [Ballard Press: http://www.ballard.com/about-ballard/newsroom/news-releases/news03061302.aspx, 26.07.2013]
04/2013	Wind energy H_2-electrolyser inaugurated in Herten, 250 MWh_{el}, 6.5 t H_2annual capacity. [03/2013]

04/2013	FC/component suppliers expected a turnover of 100 M€ in Germany in 2013. For 2020 a turnover of 2G€ ist expected. The German production of home appliances alone shall grow to M0.14 (200 MW) by 2020. [Schiel, Johannes: VDMA: Milliardenumsatzprognose für 2020 bestärkt. 11.04.2013, In: http://www.vdma.org/article/-/articleview/1381109; 14.01.2014]
04/2013	Christian Mohrdieck, Director Drive Development FC Systems at Daimler confirmed that "*all the technical issues about the functionality of fuel cell vehicles have been solved*". Daimler aims to be selling "fully commercialized" FCVs by 2017, with costs comparable to a diesel-hybrid competitor. [Morey, 2013]
04/2013	ZSW presented an FC/Li-Ion system (peak power of 2 kW_{el}) reforming an H_2-rich gas from ethanol (consumption: 0.5 $l_{ethanol}/kWh_{el}$). Per kWh_{el} two kWh_{th} are produced. [ZSW Press Release: http://www.zsw-bw.de/uploads/media/pi04-2013-ZSW-HannoverMesse.pdf, 26.07.2013]
04/2013	Hanover Trade Fair showed that suppliers of energy storage systems are regularly becoming experts in FC and battery technology. [03/2013 WSS]
04/2013	EWE ordered 100 stationary FCs for domestic use from Ceramic FCs Ltd., Australia. [04/2013 WSS]
05/2013	Air Liquide constructed an H_2-filling statinon at Ikea Lyon to fuel the fork lifts. [04/2013 WSS]
06/2013	Ballard announced the start of marketing of new generation methanol emergency power systems with better reformers and prolonged periods between off-times. [04/2013 WSS]
06/2013	Delivery of the first of a total of ten pallet trucks with FC hybrid drive and commissioning of the first indoor H_2-refuelling facility (Linde) in Europe to DB Schenker Austria. [Linde Press: http://www.linde-mh.com/en/main_page/news/pressreleases/pressreleases_1_3392.jsp; 16.01.2014]
06/2013	EONs 'power to gas plant' in Falkenhagen, Brandenburg fed H_2- to the NG-network for the first time, the plant has the capacity to produce 360 m³ H_2/h from wind energy. [EON Press Release: http://www.eon.com/de/presse/news/pressemitteilungen/2013/6/13/power-to-gas-anlage-von-eon-speist-erstmals-wasserstoff-ins-erdgasnetz-ein.html, 26.07.2013]
07/2013	An FC of ACAL Energy Ltd. reached k10 operating hours in a test according to industrial standards, equalling 500 k-km (the performance of a good diesel engine). The FC uses a liquid, non-Pt catalyst; the DoE target for 2017 is only k5 operating hours. [http://www.-goingelectric.de/2013/07/01/news/brennstoffzelle-lebensdauer-10000-stunden/; 10.09.2013]
07/2013	GM and Honda, the two vehicle manufacturers leading in FC-patents, agreed to collaborate on FC stack design and system components to lower costs and to reduce development time. Ford, Renault-Nissan, and Daimler formed a joint development alliance in January 2013 that is aimed at creating an "affordable mass-market" FCVs by 2017. BMW and Toyota have a similar arrangement. [Brooke. Lindsay: GM and Honda join forces on fuel cell development. 03.07.2013, In. http://www.sae.org/mags/aei/rgstd/12295; 10.09.2013]
09/2013	H_2-Mobility Initiative agreed to expend the current 15 H_2-station network to 400 by 2023. The first 100 stations shall start operation during the next 4 years. [Daimler Press Release: http://media.daimler.com/dcmedia/0-921-656547-49-1636552-1-0-0-0-0-0-0-0-1-0-0-0-0-0.html; 16.01.2014]
09/2013	McPhy Energy took over Enertrag HyTec (production of electrolyser of wind energy H_2-production). McPhy and Enertrag will cooperate on wind hydrogen development. [McPhy Press Release: http://www.mcphy.com/pdf/2013-09-27-Enertrag-McPhy-de.pdf; 16.01.2016]
Q3 2013	Research on catalysts is intensified, e.g. PSI et.al. developed an aerogel made of a Pt-Pd alloy which does not need a carbon support which can easily become corroded during the common start/stop operation in city traffic or during idling; thereby compromising the function of the catalyst, which in turn shortens the service life of the entire fuel cell. This enabled the catalytic activity for oxygen reduction to be increased at the positive electrode fivefold. [Leiva, Leonid: Five times less platinum: Fuel cells could become economically more attractive thanks to novel aerogel catalyst. 09.08.2013, In: http://phys.org/news/2013-08-platinum-fuel-cells-economically-aerogel.html, 16.01.2014] Israeli company CellEra (Israel is targeting a60% replacement of its oil consumption by 2025) developed a Platinum-Free Membrane (PFM). The polymer electrolytes conduct hydroxyl ions (OH^-) rather than protons, i.e. the PFM cell is mildly alkaline, which enables the use of a low cost transition metal catalyst rather than a noble metal such as platinum. The alkaline environment is non-corrosive, enabling PFM cells to use a lightweight aluminum infrastructure, the conducting membrane is made of a relatively inexpensive polymer. [http://cleantechnica.com/2013/11/21/new-low-cost-hydrogen-fuel-cell-requires-no-platinum/; http://www.bloomberglink.com/events/fuelchoices/; 16.01.2014]

11/2013	 Toyota showed its 2015 FC sedan model (100, kW, 500 km range, energy density 3 kW/l, price 50-100 kUSD) at the Tokyo autoshow and the Las Vegas Consumer Electronics Show (01/2014). It shall be introduced on the Japanese, US and European market by 2015. Toyota has realised a 95% production cost reduction since 2002 with the Highlander SUV. There will be 20 H_2-stations in the US by 2015 and 40 by 2016 - mostly in Southern California allowing most FCV drivers to reach a station within 6 minutes. Soichiro Okudaira, chief officer of Toyota's R&D group, said that lower production costs will make FCV competitive with electric cars by 2030. At the CES, Toyota's Senior Vice President for Automotive Operations, Bob Carter, said "naysayers" who have spoken out against the technology would be proven wrong and referred to Elon Musk, founder of electric car maker Tesla Motors, Carlos Ghosn, CEO of Nissan Motor, and former Volkswagen executive Jonathan Browning by name. [http://www.usatoday.com/story/money/cars/2014/01/06/toyota-fuel-cell-range/4343589/; http://www.reuters.com/article/2014/01/15/us-autoshow-toyota-fuelcell-idUSBRE-A0E05A20140115; 16.01.2014]
05/2014	California Energy Commission funds two further stations produced by Linde. The California Air Resources Board outlined California's intention to spend 50 MUSD on getting 28 H_2-stations up and running by 2015 and as many as 100 new stations added by 2025. 19 of these stations will be built through a partnership betweetn Toyota and FirstElement Fuel Inc. by 2015. [http://www.bloomberg.com/news/2014-05-01/california-awards-46-6-million-for-hydrogen-car-stations.html, 17.09.2014]
07/2014	Linde started up a production facility with an initial annual capacity of 50 H_2-stations a year. Until now, it has built them one by one. Linde announced an order for 28 stations from Japanese gas trading company Iwatani, which put the first of its Linde stations into operation near Osaka. [http://uk.reuters.com/article/2014/07/14/linde-autos-hydrogen-idUKL6N0PP4EK20140714, 17.09.2014]
07/2014	The Japanese government plans to set up about 100 commercial H_2-stations, mainly in major cities such as Tokyo, Osaka and Nagoya, by the end of March 2016 to encourage the use of FCVs. The first station was opened in July 2014. It is operated by Iwatani Corp. (major provider of industrial gases in Japan). About 40 stations are currently planned in 11 of the 47 prefectures. [http://www.japantimes.co.jp/news/2014/07/14/business/japan-gets-its-first-commercial-hydrogen-station-for-vehicles/#.U_CbqqOrvWA, 17.08.2014]

8.4 List of participants in the Delphi study

Surname	Family name	Title	Organisation	Position	Type of organisation
Henning	Niemeyer		Spilett New Technologies GmbH	Chief Executive Officer	Consultancy
Nadine	Hölzinger		Spilett New Technologies GmbH	Chief Executive Officer	Consultancy
N.N.					Fleet operator / User
Mike	Hutmacher		Spilett New Technologies GmbH	Consultant	Consultancy
Simon	Whitehouse		PE International		Consultancy
Nicole	Whitehouse		PE International		Consultancy
Bernd	Sackmann		BSR	Head of Unit	Fleet operator / User
Kai	Groth		BSR	Head of Department	Fleet operator / User
N.N.				Logistic expert	Fleet operator / User
Burkhard	Eberwein		BVG	Head of Department	Fleet operator / User
Horst-Jürgen	Rösgen		Senate of Berlin	Head of Department (retired)	Public administration & associations
Henrik	Colell	Dr.	Heliocentris Fuel Cells AG	Chief Executive Officer	FC/ H_2 system development
Joachim	Krömer	Dr.	borit	Head of Sales	FC/ H_2 system development
Klaus	Birk		ProtonMotor Fuel Cell GmbH	Sales Manager	FC/ H_2 system development
Roland	Krüger	Dr.	Ford Werke GmbH	Electric Vehicles - Basic Design	Vehicle manufacturer
N.N.					Vehicle manufacturer
Klaus	Bonhoff	Dr.	NOW	Chief Executive Officer	Public administration & associations
Johannes	Töpler	Dr.	DWV – Deutscher Wasserstoffverband	Chairman of the Board	Public administration & associations
Jeffrey	Seisler	Dr.	Clean Fuels Consulting	Chief Executive Officer	Consultancy
Carsten	Retzke		Total Deutschland	Head of Department	Mineral oil / Energy company

Surname	Family name	Title	Organisation	Position	Type of organisation
Roland	Dold		Daimler	Truck Product Engineering	Vehicle manufacturer
Ulrich	Wagner	Prof. Dr.	DLR	Vorstand für Energie und Verkehr	University / R&D institute
Thomas	Grube		Forschungszentrum Jülich GmbH	Institut für Energiever-fahrenstechnik	University / R&D institute
Bernd	Ober-schachtsiek		Zentrum für Brennstoff-zellenTechnik GmbH	Leitung der Abteilung "Wasserstofftechnik"	University / R&D institute
Daniel	Hustadt		Vattenfall Europe Innovation GmbH	Projektleiter Inno-vative Energiesysteme	Mineral oil / Energy company
Andreas	Ziolek	Dr.	Nordrheinwestfalen	Energieagentur NRW	Public administration & associations
Christian	Gruber		MAN	Abt. TVGP	Vehicle manufacturer
Andreas	Jahn			Senior Energy Expert	Consultancy
N.N.					Mineral oil / Energy company
Ronald	Grasmann		Daimler AG	Head of Dep. – Strategic Energy Projects & Market Dev. eMobility	Vehicle manufacturer
Hans-Christian	Wagner		BMW	Projektleiter CEP bei BMW (retired)	Vehicle manufacturer
N.N.					University / R&D institute
Sven	Geitmann		Hzwei	Journalist	Public administration & associations
Ulrich	Bünger	Prof. Dr.	Ludwig-Bölkow-Systemtechnik GmbH	Geschäftsführer	University / R&D institute
N. N.					Public administration & associations

8.5 Accompanying letter, first questioning round

Dear Sir or Madam,

I would like to invite you to take part in my doctoral research project "**Market introduction of hydrogen as a fuel**". I would appreciate it if you could take part in this Delphi-Analysis to share your opinion and experience on

- the main drivers, drawbacks and competing technologies influencing the market introduction process of hydrogen fuel,
- the measures that could support the market introduction of hydrogen fuel as well as
- the main timeline of the market introduction process.

A Delphi-Analysis is a widely applied and accepted method for knowledge capture and consensus building. It is used in a variety of social, managerial and technological areas. In a structured process, the Delphi-Analysis asks individuals anonymously and independently of each other for their prognosis of the future using a questionnaire. The results of the group are shared with the participants before the next questioning round starts. This allows a group judgement to be obtained without being influenced by opinion formers. The Delphi-Analysis is usually applied when there is incomplete knowledge about a topic. It allows the understanding of problems, opportunities and solutions to be improved or to forecasts to be developed.

Within this Delphi-Analysis it is planned to send out two questionnaires. After the first consultation round you will receive a summary of the results of the group's opinion to form the basis for answering the second questionnaire.

This feedback and all results are done anonymously and all information provided by you individually is kept confidential. However, I would be pleased, if you would allow me to publish your name, company and position in a list to be sent to all participants and to be used in my thesis.

In addition, a final report on the Delphi findings will be produced, the results of which will be sent to you as a copy.

The enclosed questionnaire (file: Delphi analysis 1.0 English version.xls) represents the first stage of this two-stage process. I anticipate that completing this questionnaire should take approximately one hour of your time. Please do the following after evaluating each individual idea or statement presented:

- Rate each statement according to the dimensions identified for each section.
- Add comments that extend or otherwise clarify the statement presented.
- Describe any new ideas not already included in the questionnaire that you feel are important.

I hope to receive your completed questionnaire before **11.08.2010** by e-mail (renate.lemke@ewetel.net), fax (+49-30- 536 796 60) or ordinary mail (Renate Lemke, Freiligrathstraße 24, 15366 Neuenhagen). Thank you again for your willingness to participate!

If you have any questions about the Delphi process or if you need any advice on completing this questionnaire please contact me by email (renate.lemke@ewetel.net) or telephone (+49-3342-209482).

I hope to have all the results from the first consultation round compiled by 31.08.2010 when you can expect to receive the results.

I thank you for your interest and participation.

Yours faithfully, Renate Lemke

8.6 Accompanying letter, second questioning round

Dear Sir or Madam,

First of all, thank you very much for answering the first questionnaire for my dissertation project with the topic of “Market introduction of hydrogen as a fuel”. After prolonging the deadline, I received **86% of all questionnaires sent out** (in total 36 questionnaires). The wait was worthwhile!

Please find enclosed a summary of the results of the first questioning round. Your answers are presented using the statistical parameters median and mean; the distribution of the answers is visualised using distribution and box plots (The statistical methods are explained in the summary).

In addition, I have summarised your comments on the individual questions. They partly reflect a large diversity of opinions, but also show for some questions a high level of agreement within the group of experts. A list of the participating experts is attached at the end of the summary. *Unfortunately, I did not receive confirmation of your agreement or disagreement as to the publication of your name, company and position within the company. I would therefore be pleased, if you could add this data in the framework of the second questioning round. [optional]*

A detailed evaluation and interpretation of the results as well as a comparison with literature data will only be elaborated at the end of the second questioning round. Therefore, they are **not** included at this stage.

I also enclose the questionnaire of the second (and last) round. This questionnaire mainly contains the same questions as the first one - only three questions are completely new -others have been specified on the basis of your comments or definitions have been added (all changes in the wording of the questions have been marked in *italics*.)

For each question the median[307], mean or frequency of quotation in the sample as well as your own answer from the first round is given. This procedure should allow you - together with the summary of results – to compare your answer with the group’s result. You have the possibility to reflect your answer (anonymously) with the group’s result and to reconsider your answer. In the following you may confirm your first answer or change it on the basis of new findings. (The influence of the group’s result from the first questionnaire on your answer in the second questioning round is a fundamental aspect of the Delphi-method.)Please do the following after evaluating each individual idea or statement presented:

- Rate each statement according to the dimensions identified for each section. Please mark **only one answer per question**.
- Add comments that extend or otherwise clarify the statement presented.

Also, the answers of the second questioning round as well as all other results are made anonymously and all individual information submitted by you is kept confidential.

I hope to receive your completed questionnaire before **19.11.2010** by e-mail (renate.lemke@ewetel.net), fax (+49-30- 536 796 60) or ordinary mail (Renate Lemke, Freiligrathstraße 24, 15366 Neuenhagen). Thank you again for your willingness to participate!

If you have any questions about the Delphi process, or if you need any advice on completing this questionnaire, please contact me by e-mail (renate.lemke@ewetel.net) or telephone (+49-3342-209482).

I hope to have all the results from the second consultation round compiled by the end of the year. The detailed report should be ready by the end of February 2011, when you can expect to receive the results.

I thank you for your interest and participation. Yours faithfully, Renate Lemke

[307] The median of a sequence of an uneven number of figures which have been sorted by their value is the value which halves the sequence in the middle, e.g. the median of the sequence 1, 7, **8**, 12, 27 is 8. (The sequence consists of five figures, the third and middle one, the “eight“, halves the sequence (two figures left and to figures right of it). The median is - in comparison with the mean - much less sensitive against outlying values (the mean of the example is “eleven“).

8.7 Second Delphi questionnaire, individual example

Delphi - Questionnaire on the market introduction of hydrogen fuel

Your individual responses to the Delphi expert consultation will be handled confidentially and anonymously.

!Please mark only one answer per question!

Use of various alternative technologies for different vehicle classes by 2030

1 The use of fuel cell technology will be important for the application in ... (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
a) cars and light duty vehicles					✓	5	5	
b) buses of the public transport					✓	5	5	
c) trucks of the national and international freight transport				✓		2	5	FCs, it is hard to see what else will replace diesel.

2 The use of hydrogen internal combustion engine technology will be important for the application in ... (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
a) cars and light duty vehicles		✓				2	2	
b) buses of the public transport			✓			2	3	We do know these work - although no OEM's shc
c) trucks of the national and international freight transport		✓				2	2	

3 350 bar gaseous compressed hydrogen storage technology will be important for the application in ... (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
a) cars and light duty vehicles				✓		3	4	Interim measure?
b) buses of the public transport				✓		4	4	
c) trucks of the national and international freight transport			✓			2	4	

4 700 bar gaseous compressed hydrogen storage technology will be important for the application in ... (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
a) cars and light duty vehicles					✓	5	5	
b) buses of the public transport				✓		4	4	
c) trucks of the national and international freight transport			✓			2	5	

5 Liquid hydrogen storage technology will be important for the application in ... (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
a) cars and light duty vehicles				✓		2	5	Storage issues are improtant for the implementat
b) buses of the public transport			✓			2	3	
c) trucks of the national and international freight transport			✓			2	5	

6	**Biofuels of the second generation will be important for the application in ...** (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
	a) cars and light duty vehicles				✓		4	4	*Biofuels of the second generation are using all parts of a plant or waste materials. Doing so, the efficiency is increased and a competition with food is avoided.*
	b) buses of the public transport				✓		4	4	
	c) trucks of the national and international freight transport				✓		4	4	

7	**Pure battery-electric propulsion will be important for the application in ...** (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
	a) cars and light duty vehicles					✓	4	5	
	b) buses of the public transport		✓				2	3	
	c) trucks of the national and international freight transport	✓					1	2	The median's for trucks is interesting throughout. Clearly bio-fuels would be front runner as an extender?

Changes in the German vehicle market by 2030

8	**Future new registrations of cars according to fuels in % in Germany** - hybrids and biofuels are subordinated to the respective fuel concept, see also question 9 & 10 - about 40,000 cars equals 1% (please estimate future fuel shares)	2008	2020	2030	Group's mean 2020	Group's mean 2030	own judgement 2020	own judgement 2030	Comments
	a) gasoline	54.9%	40.0%	32.0%	46%	39%	40%	20%	I have modified figures downwards in terms of alternative fuels but not as much as the 1st round medians because I believe oil shocks are very very likely in this time frame which will put pressure on the devleopment and implementation of alternatives.
	b) diesel	44.1%	37.0%	29.0%	45%	39%	35%	15%	
	c) LPG	0.5%	2.0%	2.0%	2%	3%	1%	2%	
	d) CNG	0.4%	2.0%	2.0%	2%	3%	1%	2%	
	e) electric battery vehicle	0.0%	12.0%	22.0%	3%	7%	13%	35%	
	f) hydrogen	0.0%	6.0%	12.0%	2%	9%	10%	25%	
	g) others	0.2%	1.0%	1.0%	1%	1%	1%	1%	
	Sum (control)	100.0%	100%	100%					

9	**Future hybridisation rate of newly registered cars in Germany** (*additional energy storage with a minimum capacity of 5 kW elec., independent from the fuel used*) (please estimate future hybridisation rate)	2008	2020	2030	Group's mean 2020	Group's mean 2030	own judgement 2020	own judgement 2030	Comments
	hybridisation rate	0.2%	40.0%	80.0%	14%	37%	50%	100%	Again, I believe a range of factors will lead to wholesale hybridisation.

10	**Biofuels will have a German total market share of . . .** Directive 28/2009 on the promotion of renewable energies asks for a 10% share of renewables of the gross final energy consumption in the EU transport sector by 2020 (please estimate in % energy content)	2009	2020	2030	Group's mean 2020	Group's mean 2030	own judgement 2020	own judgement 2030	Comments
	Share of biofuels	5.3%	10.0%	15.0%	11%	17%	10%	10%	Depends on availability of feed stock.

11	Future new registrations of cars according to segments in % in Germany (please estimate future segment shares)	01-04. 2010	2020	2030	Group's mean 2020	Group's mean 2030	own judgement 2020	own judgement 2030	Comments
	a) Minis and small cars	27%	35.0%	40.0%	32%	36%	35%	38%	
	b) Lower-medium class cars	43%	45.0%	50.0%	41%	38%	50%	52%	
	c) Upper medium-upper class cars	5%	5.0%	4.0%	5%	5%	5%	5%	
	d) others (SUVs, utilities, vans, sportcars etc.)	26%	15%	6%					*The difference is calculated automatically.*

12	Future new registrations of cars according to motorisation in % in Germany (please estimate future motorisation shares)	2008	2020	2030	Group's mean 2020	Group's mean 2030	own judgement 2020	own judgement 2030	Comments
	a) up to 50 kW	7%			9%	12%	0%	0%	
	b) 51 - 90 kW	46%			48%	49%	0%	0%	
	d) 91 - 130 kW	35%			32%	30%	0%	0%	
	f) 131 - and more	13%			11%	9%	0%	0%	
	Sum for controlling	100%							

13	In Germany hydrogen transport fuel will be produced ... by 2030 (please estimate share in %)	2010*	2020	2030	Group's mean 2020	Group's mean 2030	own judgement 2020	own judgement 2030	Comments
	a) centrally in large plants	XXX	80.0%	70.0%	75%	69%	80%	70%	
	b) decentrally in small distributed units (difference to a) is calculated automatically)	XXX	20.0%	30.0%	25%	31%	20%	30%	

*only pilot projects with negligible hydrogen consumption available

14	Role of hydrogen transport fuel production procedures In Germany by 2030 (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
	a) natural gas by reforming				✓		4	4	
	b) electrolysis using conventional national electricity mix			✓			3	4	
	c) electrolysis using renewable electricity from wind energy or photovoltaics being at the same time an energy storage medium					✓	5	5	
	d) chemical processes as a residue			✓			3	4	
	f) biomass by gasification or liquid reforming			✓			3	4	
	g) *elektrolysis using electricity from coal power plants in combination with CCS*		✓						*new option*
	h) *thermo-chemical processes (above 1.700 °C water vapour dissociates to hydrogen and oygen*								*Can't comment*

15	Future role of biofuels in Germany (by 2030) -EU targets using 20% of renewable energy in all economic sectors and 10% in the transport sector by 2020; -Directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for transport asks for an admixing of a minimum of 5.75% renewables to petrol or diesel fuel (please mark the importance)	Not at all important	Low importance	Neutral	Important	Very important	Group's median	own judgement	Comments
	a) Pure use of biodiesel						2		Can't comment on this set of questions
	b) Use of ethanol E85 (mixture of 85% ethanol and 15% gasoline)						2		
	c) Admixture of biodiesel to diesel						4		
	d) Admixture of ethanol to gasoline						4		
	e) Admixture of biogas to natural gas						4		
	f) Use of second generation biofuels (BTL: Biomass-to-Liquid)						4		

Period within which the event / development will first have occurred

1 = between 2010 and 2014, 2 = between 2015 and 2019; 3 = between 2020 and 2024; 4 = between 2025 and 2029; 5 = 2030 and later; 6 = never

No.	Item	between 2010 and 2014	between 2015 and 2019	between 2020 and 2024	between 2025 and 2029	2030 and later	never	Group's median	own judgement	Comments
16	**Peak Oil is reached** Peak of the entire planet's oil production. After Peak Oil, the rate of oil production on Earth would enter a terminal decline. (please mark)							2	4	
17	**The average weekly all countries crude oil spot price weighted by estimated export volume reaches 200 US$ per barrel** Maximum July 2008: 137 US$/barrel, currently about 80 US$/barrel (please mark)							3	5	
18	**One million fuel cell vehicles are produced annually (worldwide)** *(at least 4 wheels, no wheel chairs etc.)* (please mark)							4	6	

!!!Please mark only one answer!!!

At the moment chosen ....

Item	China	EU	India	Japan	USA	others	most frequent entry	own judgement	Comments
a) Fuel cell / H_2 technology development leading country is ...							2	2	
b) Plurality of fuel cell vehicles is manufactured in ...							4	4	
c) Most important market is ...							1, 2, 4	1	

No.	Item	between 2010 and 2014	between 2015 and 2019	between 2020 and 2024	between 2025 and 2029	2030 and later	never	Group's median	own judgement	Comments
19	**One million battery electric vehicles are produced annually (worldwide)** *(at least 4 wheels, no wheel chairs etc.)* (please mark)							3	5	

!!!Please mark only one answer!!!

At the moment chosen ....

Item	China	EU	India	Japan	USA	others	most frequent entry	own judgement	Comments
a) Battery electric car technology development leading country is ...							1	2	
b) Plurality of battery electric vehicles is manufactured in ...							1	1	
c) Most important market is ...							1	1	

20 The following new technologies are maturely technologically developed
(please mark)

No.	Item	between 2010 and 2014	between 2015 and 2019	between 2020 and 2024	between 2025 and 2029	2030 and later	never	Group's median	own judgement	Comments
20	a) hybridisation of vehicles with spark ignition engine							1.5	5	
	b) hybridisation of vehicles with compression ignition engine							2	6	
	c) heavy duty natural gas compression ignition engine							3	6	
	d) spark-ignition-engine operated by a hydrogen-natural gas blend							2	6	
21	**EU carbon trading costs reaches 25 €/Mg CO_2** *(assumption: inlcuding only current group of emitters)* Current carbon trading costs are about 13 €/Mg CO_2 of EU allowances (please mark)							2	3	
22	**CO_2 sequestration, capture & storage technology is regularly applied in Germany** (please mark)							4	6	
23	**Significant number of large German cities close their urban centres for private vehicles or have installed a congestion charging system to control car entry** (please mark)							3	4	
24	**Green party platform issues dominate European politics, increasing the respective regulatory power** (please mark)							6	6	

Please express your level of agreement (time horizon until 2030)

1 = strongly disagree, 2 = disagree, 3= neutral, 4 = agree, 5 = strongly agree

No.	Statement	strongly disagree	disagree	neutral	agree	strongly agree	Group's median	own judgement	Comments
25	**Car will stay the most important passenger transport mean** (please mark)						4	5	
26	**In the future innovative technologies are the most important tool against climate change** (please mark)						4	4	
27	**In the future strict governmental standards** *(including all rise in costs of CO_2-emissions)* **are the most important tool against climate change**						4	5	
28	**In the future consumer behaviour is guided by the concept of sustainable development and environmental consciousness. Company's Corporate Social Responsibilities will become important for company's success** (please mark)						4	4	*In accordance with the so-called Brundlandt-Report sustainable development is defined as: "to make development sustainable [is] to ensure that it meets the needs of the present without compromi-sing the ability of future generations to meet their own needs". (http://www.un-documents.net/ocf-ov.htm#I.3)*
29	**Costs of environmental protection measures and use of resources are increasing dramatically and have an increasingly negative effect on companies' profits** (please mark)						4	1	
30	**Customers are ready to pay a premium for "green" products and services of up to 20%** (please mark)						3	3	
31	**In the future sustainable products and services provide significant share** ***(>10%)*** **to the national GDP** (please mark)						4	4	*Sustainable products &services shall comply in terms of efficiency and environmental friendly-ness to the state of the art, i.e. use up-to-date processes, equipment and operation methods*
32	**Emerging countries undergo change in consciousness and policy supporting environmental and climate change measures** (please mark)						4	4	
33	**In the future emerging economies skip some innovation/technology levels and enter directly to advanced technologies reducing their CO_2 emissions** (please mark)						4	2	
34	**In the future alternative urban freight transport systems are implemented, e.g. tube systems,** ***joint company*** **distribution centres etc.** (please mark)						3	4	
35	**In the future large infrastructure projects -** ***e.g. H_2-infrastructure, recharging points for electric vehicles, streets*** **- are mainly privately financed** (please mark)						3	2	

What specific short- to long-term actions could be undertaken to further promote the market introduction of hydrogen fuel?

a) Importance: How essential would this measure be for the market introduction of hydrogen fuel?
1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 =Important; 5 = Very Important

b) Urgency: How imperative is the need for the market introduction of hydrogen fuel?
1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later

c) Feasibility: How likely is it that this measure can be successfully implemented in a meaningful timeframe?
1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

36 Implement standards to define vehicle filling, e.g. adapter, pressure curve, pre-cooling temperature

(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						5	4	
b) Urgency						3	5	
c) Feasibility						5	5	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

37 Reliable mineral oil tax exemption for hydrogen as a fuel for at least 10 years

(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						5	4	
b) Urgency						3	4	
c) Feasibility						4	3	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

38 Unbureaucratic direct subsidies to fleet and private fuel cell car purchasers, e.g. 5,000 €/car

(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						4	5	
b) Urgency						3	5	
c) Feasibility						3	1	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

39 Public co-funding of hydrogen infrastructure beyond the first demonstration projects

(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						5	5	
b) Urgency						3	1	
c) Feasibility						4	3	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

40 Early decision on further tightening of EU car fleet standard from 130 g CO_2/km in 2012 and 95 g CO_2/km in 2020 to e.g. 75 g CO_2/km in 2030

75 g CO_2/km equals an average consumption of 2.9 l diesel/100 km or 3.1 l/gasoline/100 km

(please mark)

	1	2	3	4	5	median	gement	Comments
a) Importance						4	3	
b) Urgency						3	4	
c) Feasibility						4	2	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

41 Inclusion of transport into the Emission Trading Scheme of the EU

(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						4	3	
b) Urgency						3	4	
c) Feasibility						4	2	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

42 Products and services are regularly labelled according to their CO_2-footprint
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						4	3	
b) Urgency						3	4	
c) Feasibility						4	2	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

43 International mandatory targets for further CO_2-reduction beyond 'Kyoto-agreement' are available and kept by nations
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						5	4	
b) Urgency						3	3	
c) Feasibility						3	3	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

44 Introduce strong CO_2-component to the granted tax concessions for commercially and privately used company cars
(please mark)

In Germany, about 60% of the newly registered cars are registered commercially, but the total car pool is 90% privately owned

	1	2	3	4	5	median	gement	Comments
a) Importance						4	4	
b) Urgency						3	2	
c) Feasibility						4	3	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

45 Implement information platform for fuel cell vehicle users and purchasers comparable to German national "Erdgasinitiative"
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						4	3	
b) Urgency						3	3	
c) Feasibility						4	3	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

46 Include maintenance and repair of fuel cell vehicles as well as safe garage operation and equipping to the education of new service staff
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						5	5	
b) Urgency						3	3	
c) Feasibility						5	5	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

47 Train existing maintenance and repair personnel to service fuel cell vehicles
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						5	5	
b) Urgency						3	4	
c) Feasibility						5	5	

Importance: 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
Urgency: 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
Feasibility: 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

48 Train sales personnel to better market fuel cell vehicles among conventional vehicles
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						4	5	
b) Urgency						3	2	
c) Feasibility						4	5	

a) 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
b) 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
c) 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

49 Organise symposia at professional society meetings to stimulate further research and co-operation on fuel cell vehicle technology and infrastructure development
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						4	3	
b) Urgency						3	2	
c) Feasibility						5	5	

a) 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
b) 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
c) 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

50 Elaboration of an inventory of new information, research underway, and potential funding sources on national and European level
(please mark)

	1	2	3	4	5	Group's median	own judgement	Comments
a) Importance						4	5	
b) Urgency						3	1	
c) Feasibility						4	5	

a) 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
b) 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
c) 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

New

51 Payment of an "H_2-Cent" - charged from each litre of gasoline or diesel sold - to the building-up of a hydrogen infrastructure
(please mark)

	1	2	3	4	5	Comments
a) Importance						
b) Urgency						
c) Feasibility						

a) 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
b) 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
c) 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

52 Financial support to the production of regenerative hydrogen
(please mark)

	1	2	3	4	5	Comments
a) Importance						
b) Urgency						
c) Feasibility						

a) 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
b) 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
c) 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

53 Procurement plan to equip the public fleet of ministries, public organisa-tions etc. with fuel cell vehicles
(please mark)

	1	2	3	4	5	Comments
a) Importance						
b) Urgency						
c) Feasibility						

a) 1 = Not at all important; 2 = Low importance; 3 = Neutral; 4 = Important; 5 = Very Important
b) 1 = 2010; 2 = 2011/2012; 3 = until 2015; 4 = until 2020; 5 = later
c) 1 = Not feasible; 2 = Somewhat unfeasible; 3 = Neutral; 4 = Somewhat feasible; 5 = Very feasible

Thank you for your participation

8.8 Summary of results of the second Delphi questioning round[308]

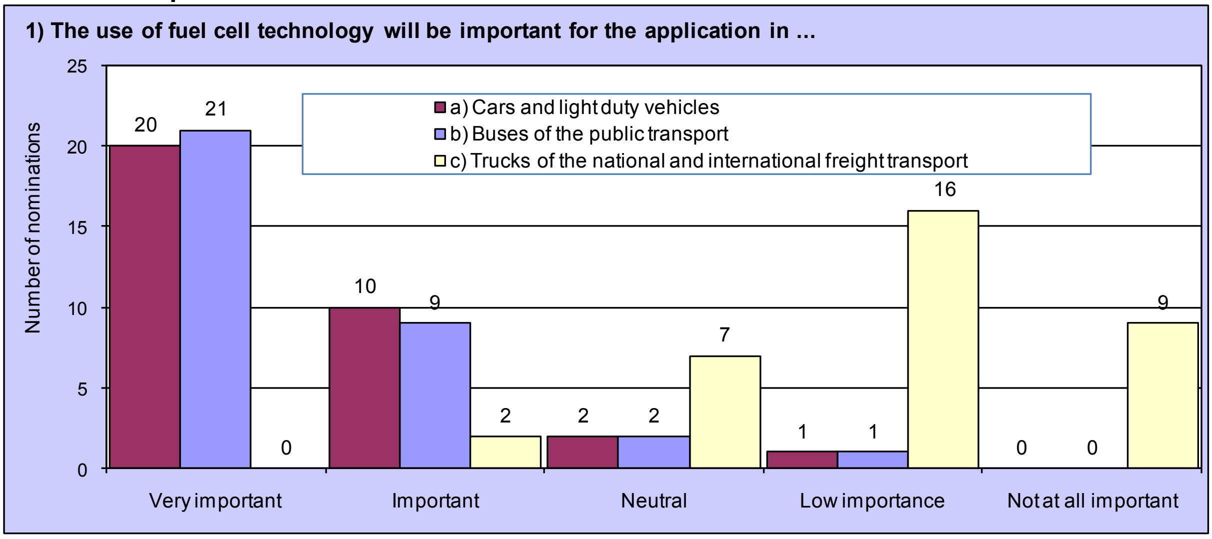
Use of various alternative technologies for different vehicle classes by 2030

Q1: The use of fuel cell technology will be important for the application in ...

Median[309] from single answers:

Question	a) Cars and light duty vehicles	b) Public Transport Buses	c) National and international freight transport trucks
Median	5	5	2
Text in clear	Very important	Very important	Low importance

Distribution plot:



Comments:

a) Cars and light duty vehicles

- This may come after b & c and be complemented by battery electric cars if the national grids are cleaned up.
- PEMFC with H_2 in pressurised tanks or cryogenic storage.[310]
- No local emissions, high efficiency, fuel with a wide primary energy base.
- Need for H_2-fuelling infrastructure reduces short & mid-term potential.
- Propulsion / Range Extender.
- *The size of the fuel cell system & added expense will continue to be a long term impediment*.[311]

b) Public transport buses

- Already nearing pre-commercial stage.
- PEMFC with H_2 in pressurised tanks or cryogenic storage.
- No local emissions, high efficiency, fuel with a wide primary energy base.
- Ability to fuel centrally increases potential and importance.

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308 In the framework of the Delphi Analysis a bilingual version was returned to the experts; in the following only an English version is given.

309 The **median** is the numeric value separating the higher half of a sample from the lower half, i.e. it is the middle value of a set of sorted data containing an odd number of values or the average of the two middle values of a set of data with an even number of values, e.g. the median of the sequence 1, 7, **8**, 12, 27 is 8. The median could be used, if open time horizons are requested from the expert panel (question 16-24). In comparison to the mean, the median reacts less sensitively to exceptions, e.g. the mean of the example is 11. If the sequence follows a Gaussian distribution, mean and median rates to the same value.

310 Cross references have been supplemented –as far as possible.

311 Comments marked in italics have been made during the second round of questioning.

- Propulsion / Range Extender.
- *Public funding and larger fuel cell systems for this sector could remain popular.*
- *Precondition: Scaling-effects from the car market*.

c) National and international freight transport trucks
- Research well underway.
- There is only a small chance that HDVs will be propelled with H_2 in international freight transport.
- Rather irrelevant for propulsion due to storage H_2-density and high efficiency of diesel ICE at constant highway driving, potential as APU (but: 2. fuel?).
- PEMFC with H_2 in pressurised tanks or cryogenic storage.
- According to H_2-infrastructure.
- Attractive essentially for APU in combination with diesel reformer.
- No suitable storage technology in sight.
- Corridor-style fuelling will take time to develop.
- Application is sensitive with payload and mileage.
- On-board power supply.

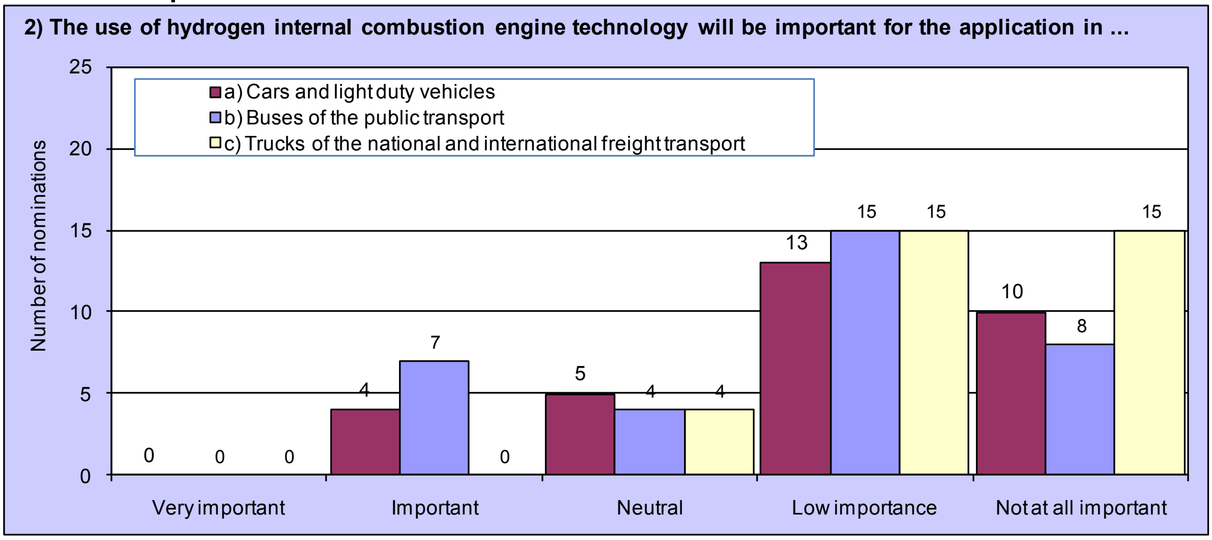
- *While these may be the last vehicles to adopt FCs, it is hard to see what else will replace diesel.*
- *For the application as APU this topic is important (4), for application as propulsion only low importance (2), in summary: average rating of 3.*
- *Range Extender / APU.*

Q2: The use of hydrogen internal combustion engine technology will be important for the application in ...

Median from single answers:

Question	a) Cars and light duty vehicles	b) Public transport buses	c) National and international freight transport trucks
Median	2	2	2
Text in clear	Low importance	Low importance	Low importance

Distribution plot:



Comments:

a) Cars and light duty vehicles
- I know of no OEM who is looking at this technology and it is, at best, an interim solution due to the existence of some emissions.
- H_2 in pressurised tanks or cryogenic storage.
- H_2 ICE will not become reality - the efficient diesel(hybrid) ICE is an alternative.
- Consumption of the more expensive fuel is too high / only low mileage possible.
- For all sectors efficiency is lower & W2W results are not as good as dedicated fuel cells.

- *Energy chain is not favourable.*
- *The energy efficiency is low.*
- *Significant consumption reduction through hybridization of low-volume H2-ICE (cars and busses).*

b) Public transport buses

- Buses with H_2 ICE have already been proven to work with much less emissions - however OEM's are not showing much interest in them despite their lower cost and interest from potential clients.
- H_2 in pressurised tanks or cryogenic storage.
- ICE will not become reality - the efficient diesel(hybrid) ICE is an alternative.
- At best during a short transformation phase until FCs become available.

- *We do know these work - although no OEM's show interest.*
- *Significant consumption reduction through hybridization of low-volume H2-ICE (cars and busses).*

c) National and international freight transport trucks

- HDVs running on hydrogen have low chances for realisation for international freight transport.
- H_2 in pressurised tanks or cryogenic storage.
- ICE will not become reality - the efficient diesel(hybrid) ICE is an alternative.
- No suitable storage technology in sight.

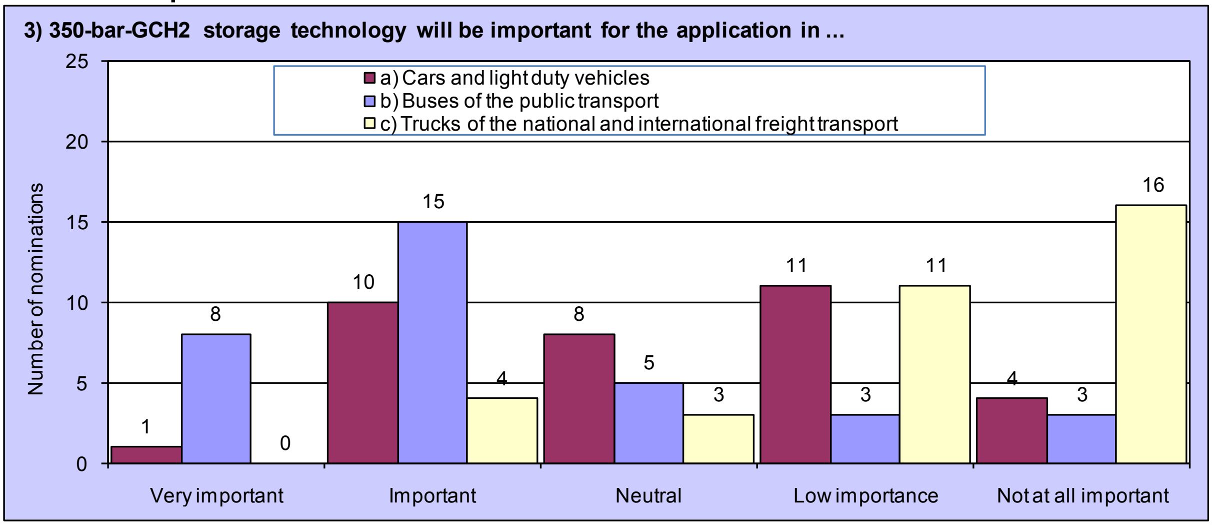
- *The efficiency is even more important on long distances for H_2-utilisation, if at all, than FCs.*

Q3: 350 bar gaseous compressed hydrogen storage technology will be important for the application in ...

Median from single answers:

Question	a) Cars and light duty vehicles	b) Public transport buses	c) National and international freight transport trucks
Median	3	4	2
Text in clear	Neutral	Important	Low importance

Distribution plot:



Comments:

a) Cars and light duty vehicles

- As an intermediate stage towards 700 bar.
- Could be rather 500 bar also for $cCGH_2$.
- Mileage is problematic.
- For larger, LDVs in local fleets, e.g. urban delivery vehicles.
- Only reasonable for vehicles with low mileage.
- Hopefully, there will some lower pressure 350-500 bar for vehicles; I am missing material handling/fork lifts

- As with CNG, vehicle range will be an important issue to overcome.
- *Declining storage technology.*
- *Interim measure?*
- *Higher valued if local transport is considered, in particular for LDVs in urban delivery.*
- *At 700 bar higher mileage and lower space necessary for the storage tanks..*

b) Public transport buses

- Different refuelling regime makes 350 bar acceptable.

c) National and international freight transport trucks

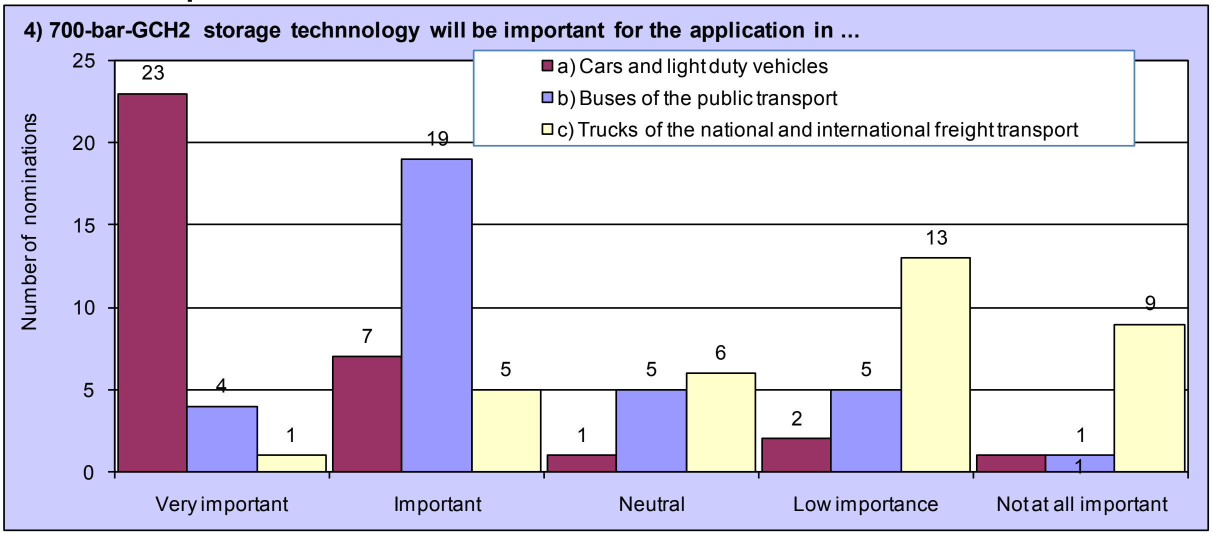
- ditto to (a) above [As a intermediate stage towards 700 bar].
- HDVs running on hydrogen have low chances for realisation.
- Mileage is not enough.
- Storage density is not high enough.
- *I don't think this will be an important sector for FCs. Whatever percentage can be captured, however, 350 bar will be as important as for other sectors.*
- *Possibly as APU.*

Q4: 700 bar gaseous compressed hydrogen storage technology will be important for the application in ...

Median from single answers:

Question	a) Cars and light duty vehicles	b) Public transport buses	c) National and international freight transport trucks
Median	5	4	2
Text in clear	Very important	Important	Low importance

Distribution plot:



Comments:

a) Cars and light duty vehicles

- Needed for range.
- See above [could be rather 500 bar for $cCGH_2$].
- Perhaps between 350 and 700 bar due to the energy balance.
- As long as there are no reasonable alternatives available.
- Cost & engineering factors for all sectors will be a challenge.
- Alternatively 500 bar.

b) Public transport buses

- For special applications (range, space available [double-decker]).
- As long as there are no reasonable alternatives available.

- Alternatively 500 bar.

- *Advantageous for buses due to large fuelling amount.*

c) National and international freight transport trucks
- Needed for range.
- Storage density is not large enough.
- See question 1 [application is sensitive concerning payload and range].

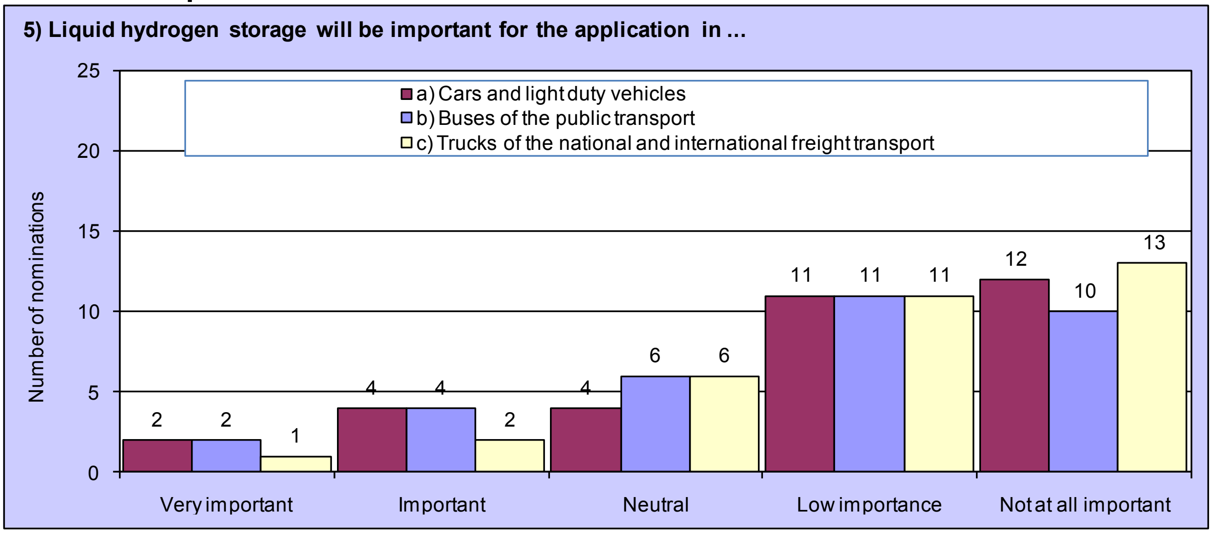
- *If H_2, then 700 bar due to H_2-demand between fuelling stops.*
- *Application has a low significance in general for FC- and H_2-ICE.*
- *Possibly for on-board supply.*

Q5: Liquid H_2-storage technology will be important for the application in ...

Median from single answers:

Question	a) Cars and light duty vehicles	b) Public transport buses	c) National and international freight transport trucks
Median	2	2	2
Text in clear	Low importance	Low importance	Low importance

Distribution plot:



Comments:

a) Cars and light duty vehicles
- The storage of LH_2 is currently not further developed.
- Due to energy efficiency reasons not a good solution.
- LH_2 energy density is much improved for all sectors. Experience with LNG will be critical to transfer.

- *Energy chain is not advantageous.*
- *Storage issues are important for the implementation of H_2-fuel in all aspects.*
- *CH_2 density is not good. At some point the industry will figure out that LH_2 will be economical. On the other hand, maybe it won't make a difference if FCs never take off as hoped.*

b) Public transport buses
- May be attractive due to high storage density; boil-off is no problem in the case of a daily use, but is eliminated due to high costs in comparison to pressurised storage.
- Not a good solution due to energy efficiency reasons.

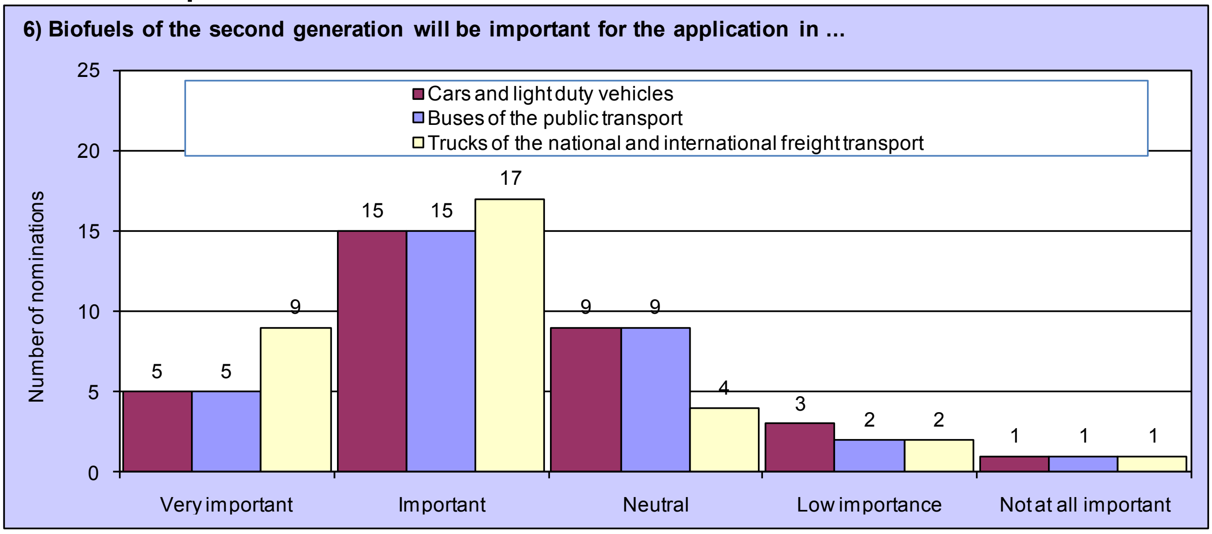
c) National and international freight transport trucks
- No sufficient energy storage density.

Q6: Biofuels of the 2nd generation[312] will be important for the application in ...

Median from single answers:

Question	a) Cars and light duty vehicles	b) Public transport buses	c) National and international freight transport trucks
Median	4	4	4
Text in clear	Important	Important	Important

Distribution plot:



Comments:

a) Cars and light duty vehicles

- For covering all mobility demands.
- Will extend the range of renewable fuels, but will not be environmentally sustainable in the long run.
- Limited potential, transmission phase.
- For a market share > 10 %.
- Due to a low share in the conventional mixture, a rather small importance in the overall context (but is has a place).
- Cannot evaluate this question.
- Focus on HDV and air traffic, because these applications rely on a high energy density.
- As blend.
- Presumably you refer to liquid biofuels? What about biomethane?
- Designed fuels for a clean combustion /CO_2-reduction.
- There will be not enough available to cover demand.

b) Public transport buses

- ditto [Will extend the range of renewable fuels but not environmentally sustainable in the long run].
- For a market share > 10 %.
- Due to a low share in the conventional mixture, a rather small importance in the overall context (but is has a place).
- Cannot evaluate this question.
- Focus on HDV and air traffic, because these applications rely on a high energy density.

c) National and international freight transport trucks

- Ditto [Will extend the range of renewable fuels but not environmentally sustainable in the long run].
- For a market share > 10 %.

312 *Biofuels of the second generation are using all parts of a plant or waste materials. Doing so, the efficiency is increased and a competition with food is avoided.*

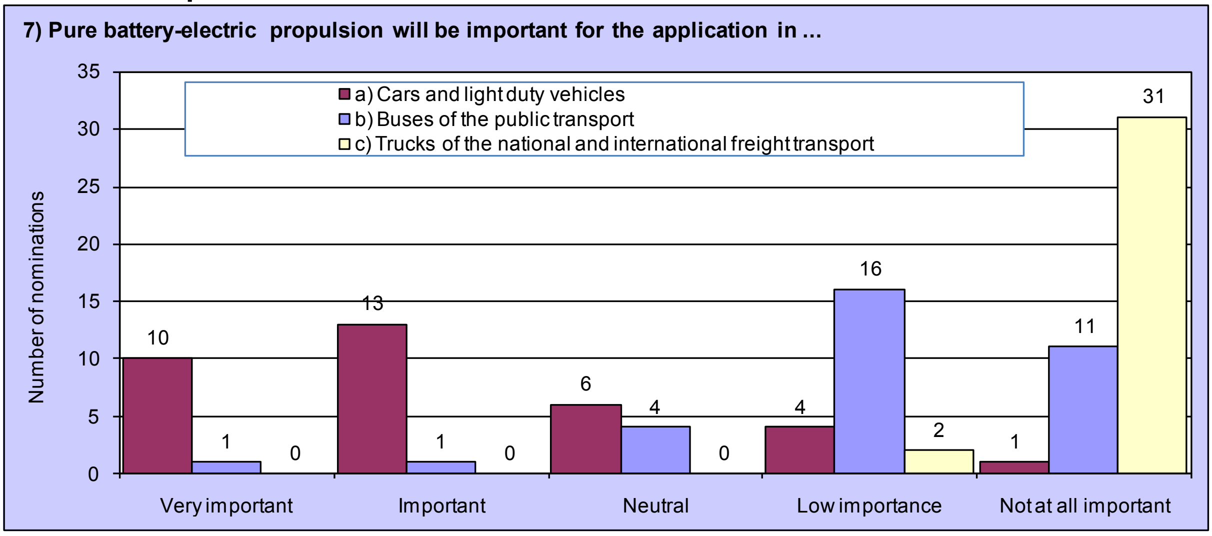
- Due to a low share in the conventional mixture, a rather small importance in the overall context (but is has a place).
- Cannot evaluate this question.
- Use of residual biomass and biomass from agriculture, if agricultural land is available.
- Would be the only CO_2 mitigation option.

Q7: Battery-electric propulsion will be important for the application in ...

Median from single answers:

Question	a) Cars and light duty vehicles	b) Public transport buses	c) National and international freight transport trucks
Median	4	2	1
Text in clear	Important	Low importance	Not at all important

Distribution plot:



Comments:

a) Cars and light duty vehicles

- Limited to urban vehicles.
- Will be in the mix for urban transport, but will need transformation of the stationary energy sources to be sustainable.
- Only vehicles for operation on short-distances.
- Cars of the compact class, low mileage.
- Hybrids, no Plug-in.
- Only for special short-distance fleets and urban vehicle applications.
- No local emissions, high efficiency, fuel with a wide primary energy base, but only vehicles with low mileage.
- Depending on car segment (city vs. upper class)
- Depending on the level of electrification.
- Only urban applications, not enough resources, increase of capacity is still not possible to predict.
- Possibly FC as Range Extender.

- *Only special niche application, similar to 3a)*
- *Only for short distances (but who needs individual transport in the City).*

b) Public transport buses

- Probably only for small commuter. Same comment as above. [Will be in the mix for urban transport in particular but will need transformation of stationary energy source to be sustainable.]
- Problem of mileage.
- Minibuses in sensitive areas (inner-city, recreation areas).
- Hybrids, no Plug-in.

- Only if the battery energy density is high enough.
- As auxiliary.
- Depending on the level of electrification.
- Possibly FC as Range Extender.

- *Range is too low, weight is too high, if it were electrical: Trolley buses are a simple and proven technology.*

c) National and international freight transport trucks
- Problem of range.
- If BEV, hybridisation plays no role.
- Hybrids, no Plug-in.
- No sufficient energy density.
- As auxiliary.
- Hybridisation.

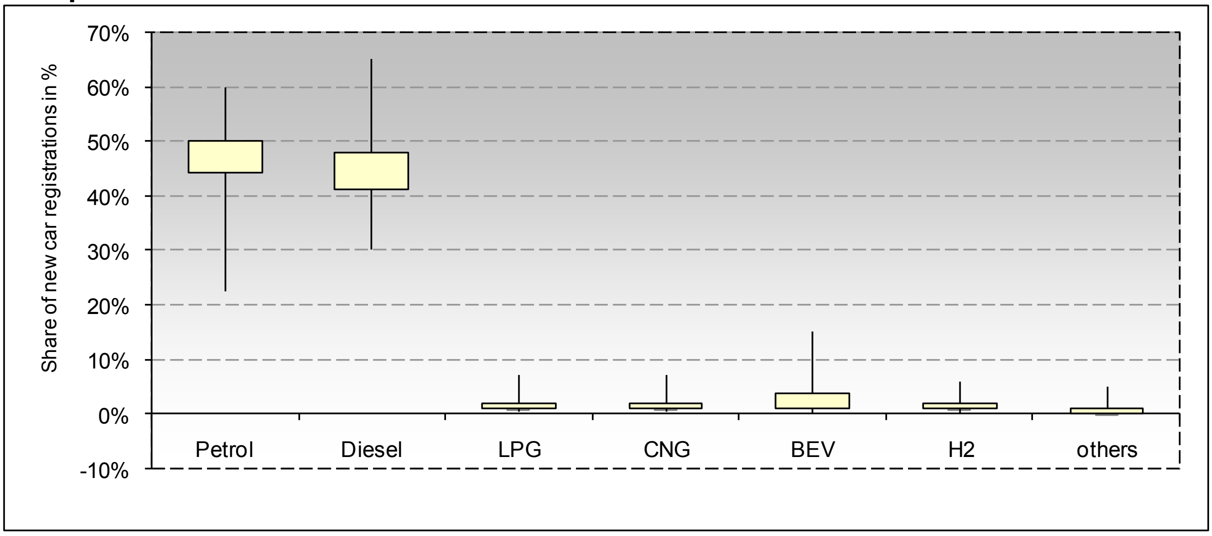
- *The medians for trucks is interesting throughout. Clearly bio-fuels would be front runner as an extender?*

Changes in the German vehicle market by 2030

Q8: Future new registrations of cars according to fuels in % in Germany

Note: hybrids and biofuels are subordinated to the respective fuel concept, see also question 9 & 10

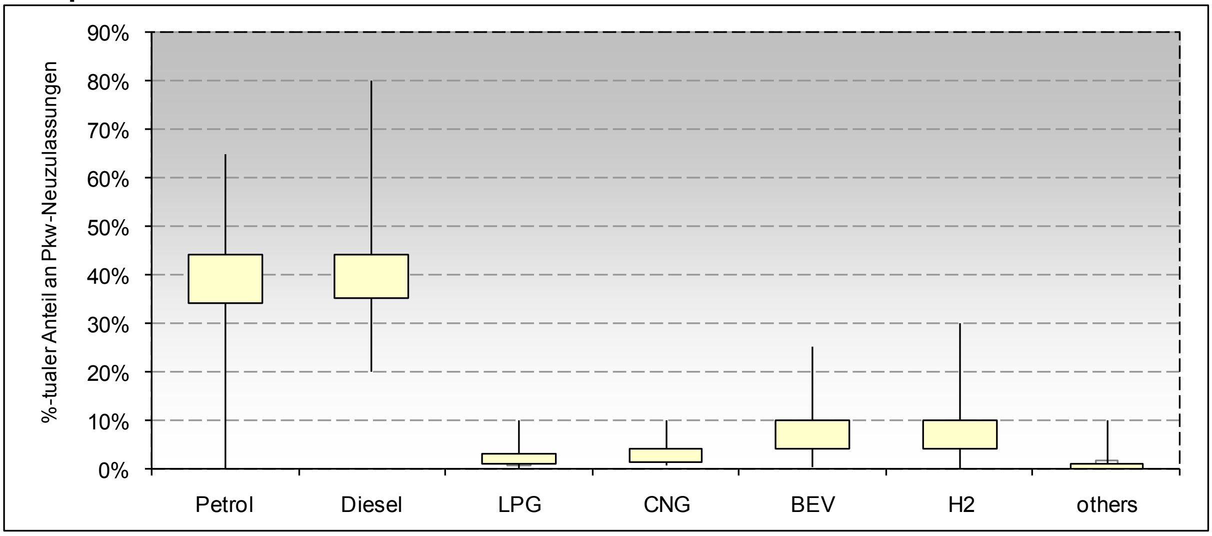
Boxplot for 2020[313] / [314]



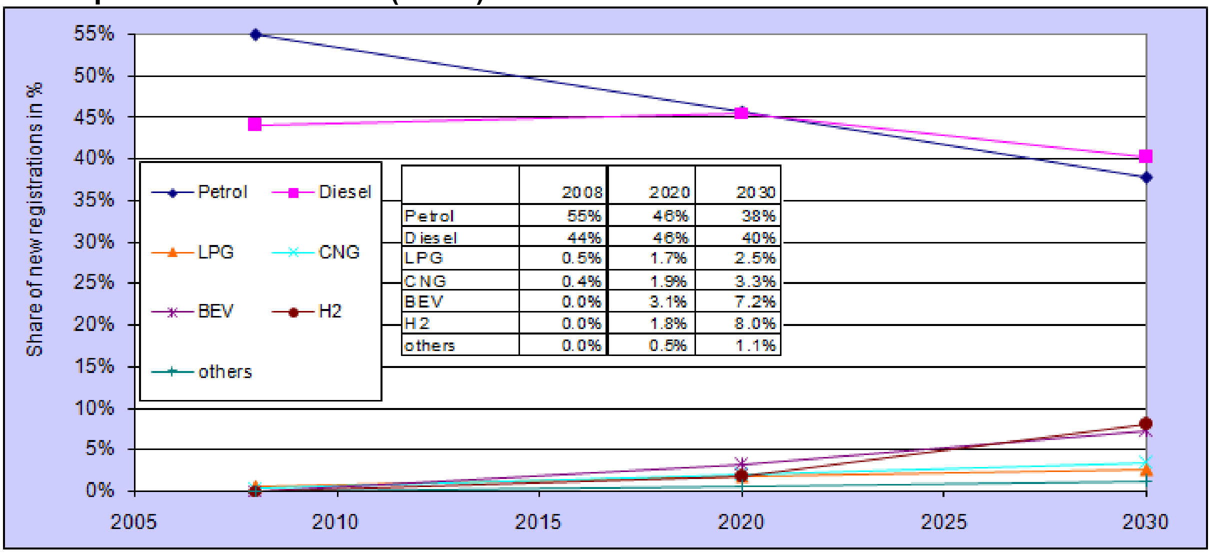
313 Boxplots summarise five numbers: the smallest observation (sample minimum), lower quartile, median, upper quartile and largest observation (sample maximum). A boxplot displays differences between populations. It consists of a box and two lines, extending the box. The end of the lower line marks the sample's minimum, the end of the upper line its maximum. 50% of all values are located within the box (inter-quartile range). The lower line of the box represents the 25%-quartile (25% of all values of the sample are smaller than this value), the upper line of the box is the 75%-quartile (75% of all values of the sample are smaller than this value). The median is marked as a line within the box. It divides the whole diagram into two parts, on both sides are 50% of all values, visualising the dispersion (spread) and skewness in the data.

314 BE: Battery-electric

Boxplot for 2030



Development of fuel shares (mean)[315]



	2008	2020	2030
Petrol	55%	46%	38%
Diesel	44%	46%	40%
LPG	0.5%	1.7%	2.5%
CNG	0.4%	1.9%	3.3%
BEV	0.0%	3.1%	7.2%
H2	0.0%	1.8%	8.0%
others	0.0%	0.5%	1.1%

Comments:

a) Petrol

- Primarily biofuels (predominately), Second Generation Fuels.
- Clearly this is fully dependent on the rate of development of alternative fuels. However, I firmly believe, once these come available at the right price they will sell very well.
- Increasingly hybrid application!
- A long life for the crystal ball!
- Spark ignition engines make up disadvantage of energy efficiency and will be increasingly combined with electrical systems.
- 2008 is a bad year for any comparison due to the scrapping bonus [Note: The Directive for Support of sales of cars of 20 February 2009 has been put in force by the German Federal government as part of the Recovery Programme II in January 2009. Thus, 2008 is the last undisturbed reference year. In earlier years the share of alternative propulsions systems has been very small and does not reflect the current developments.]
- New combustion systems (Diesotto/HCCI) soften the strict distinction between spark and compression ignition engines. It is not clear which fuel will be used (probably a specially adapted diesel), thus only a joint value is given for a general ICEs in 2030. [82%]

[315] Data from 2008: Kraftfahrtbundesamt: New registrations of cars according to fuel in 2008

- *I have modified figures downwards in terms of alternative fuels, but not as much as to the 1st round's median because I believe oil shocks are very, very likely in this time frame which will put pressure on the development and implementation of alternatives.*

b) Diesel

- In the first case biofuels (mostly), blending and direct combustion.
- Increasingly hybrids.

- *HCCI or Diesotto together, perhaps the fuel will be known quite differently, who knows????*

c) LPG

- Assuming a continuation of the tax advantage, otherwise this option will diminish.

d) CNG

- Assuming a continuation of the tax advantage, otherwise this option will diminish.

e) BEVs

- Limited to urban vehicles,
- Without PHEVs.

- *Urban applications*.

f) Hydrogen

- Infrastructure and sustainable production are still unclear.

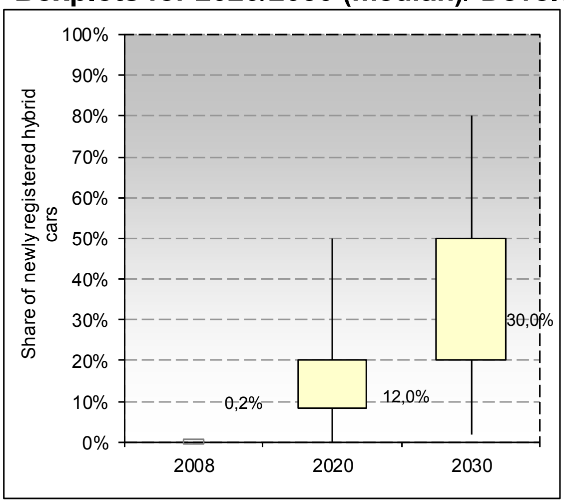
- *Because there are different users, including commercial vehicles, this is a little bit "moderated".*

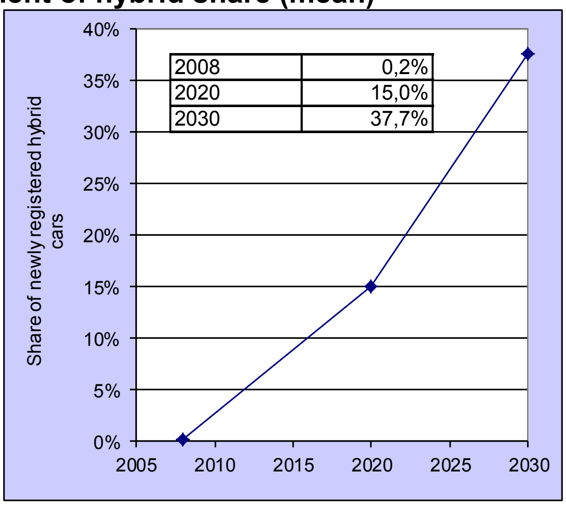
g) others

- The question covers ONLY new registrations, not vehicles in use.
- Biofuels.
- Pure biofuels?
- Plug in hybrids.
- Hybrid electric/petrol or hybrid electric/CNG.
- For example ethanol or methanol with DMFC as Range Extender.

Q9: Future hybridisation rate[316] of newly registered cars in Germany (*additional energy storage with a minimum capacity of 5 kW_{el},* independent from the fuel used)

Boxplots for 2020/2030 (median)/ Development of hybrid share (mean)[317]





Comments:

- Relates to new registrations.
- Incl. FCVs, which are 100% hybrids.

---

316 Definitions, which have been added in the second questioning round are marked in italics.

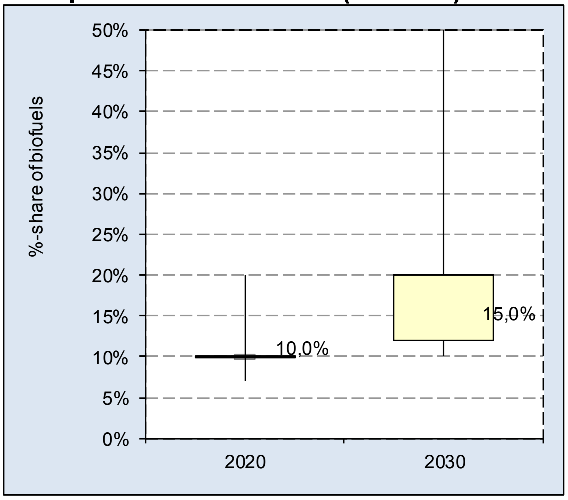
317 kba statistics on new registrations of cars according to fuel in 2008, http://www.kba.de, fz13

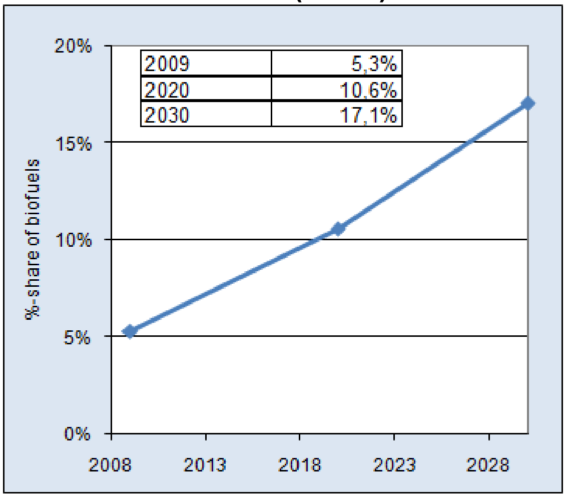
- It is not possible to answer this question properly, because even today, every car includes a battery; about 20 % of the newly registered cars use intelligent generator management and start-stop. Answer relates at least to " Mild Hybrid" with >5 kW_{el}.
- All kinds of hybridisation.
- Same problem as with the solely electric drive. The origin of the resources is unclear?

- *Again, I believe a range of factors will lead to wholesale hybridisation.*
- *Changes due to currently updated information.*

Q10: Biofuels will have a German total market share of . . .

Boxplots for 2020/2030 (median) / Development of biofuel share (mean)[318]





Comments:

- Much higher percentage for newly registered cars.
- Decreasing total market due to higher efficiencies, share of biofuels will increase.
- Cannot evaluate this question.
- Only if EU mandates remain firm.
- 2030: >50%.

- *Depends on availability of feed stock.*

Q11: Future new registrations of cars according to segment in % in Germany

Comments:

a) Mini and small cars

- This will be affected by alternative fuel development and fuel price.
- No idea.
- No big changes expected.

b) Lower-medium class cars

- Including increasing demand of more convenient vehicles due to aging of population.
- Business cars have the largest share of vehicles. This will stay medium class in the future.

c) Upper medium, upper class cars

- Luxury segment will increase.

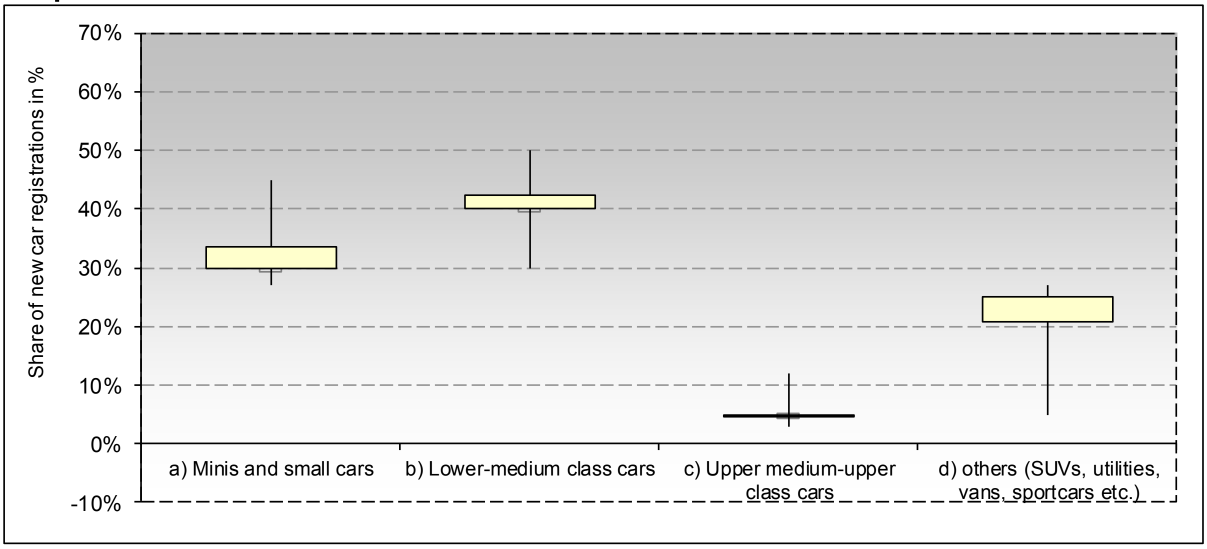
d) Others (SUVs, utilities, mini and large vans, sport cars, etc.)

- -/-
- *Coffee grounds*.

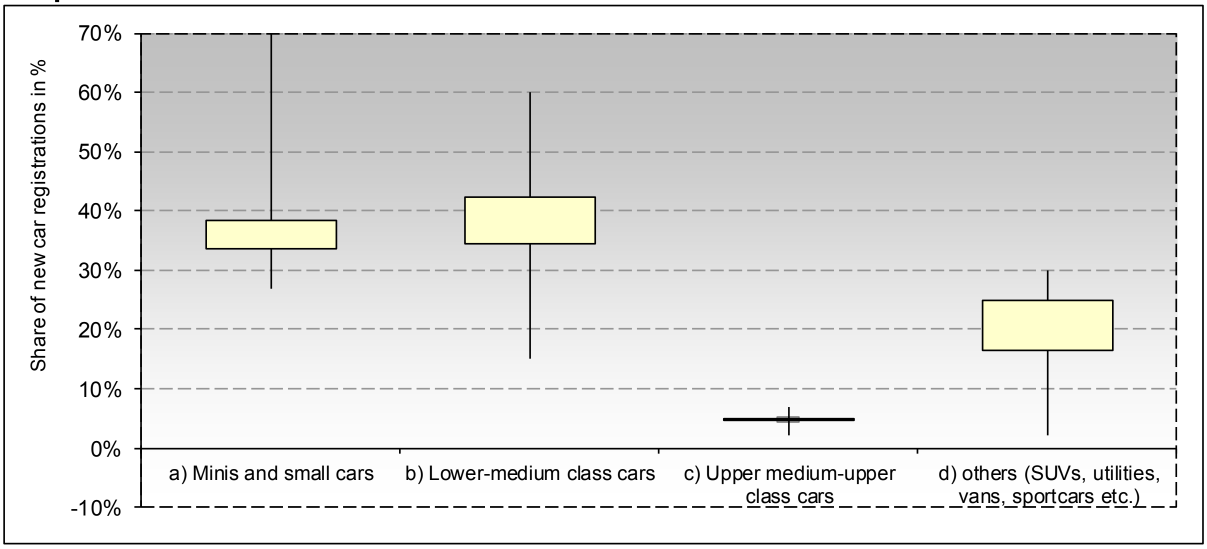
---

318 Data for 2009: Own calculation based on statistics of the Federal Office of Economics and Export Control: http://www.bafa.de/bafa/de/energie/mineraloel_rohoel/amtliche_mineraloeldaten/index.html

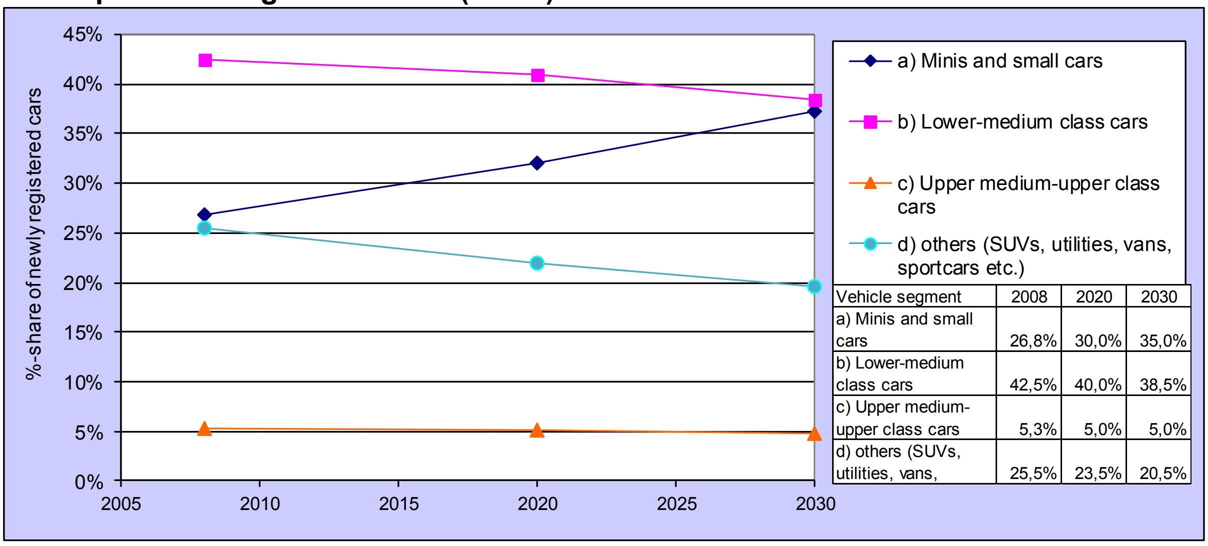
Boxplot for 2020



Boxplot for 2030



Development of segment shares (mean)[319]

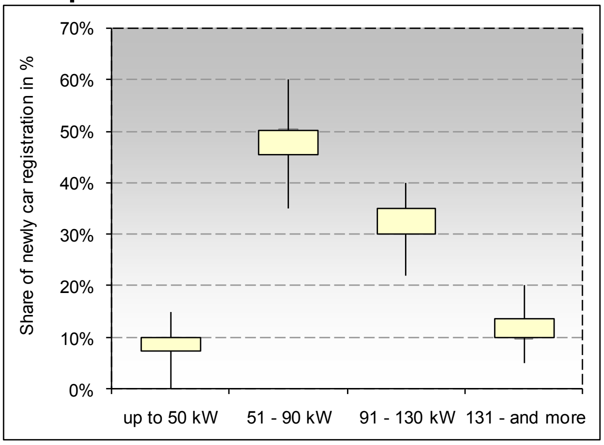


Vehicle segment	2008	2020	2030
a) Minis and small cars	26,8%	30,0%	35,0%
b) Lower-medium class cars	42,5%	40,0%	38,5%
c) Upper medium-upper class cars	5,3%	5,0%	5,0%
d) others (SUVs, utilities, vans,	25,5%	23,5%	20,5%

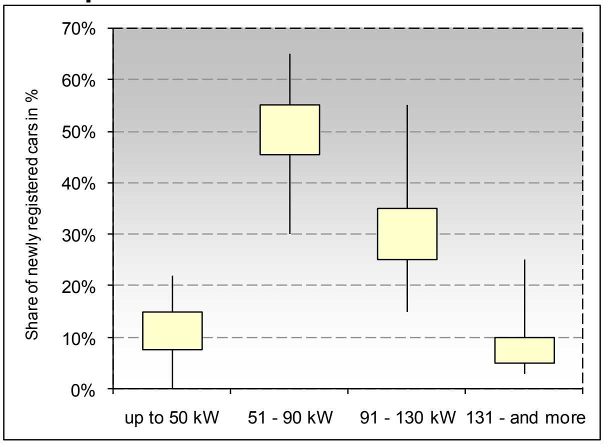
319 Kba statistics on new registrations according to segments of 2008, http://www.kba.de

Q12: Future new registrations of cars according to motorisation in % in Germany

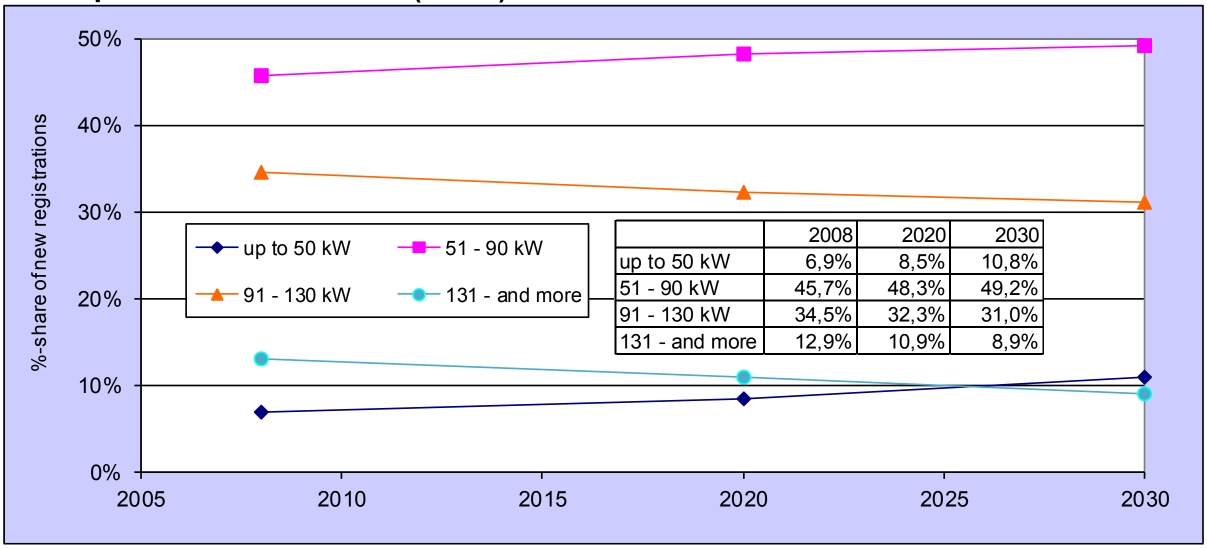
Boxplot for 2020



Boxplot for 2030



Development of motorisation (mean)[320]



	2008	2020	2030
up to 50 kW	6,9%	8,5%	10,8%
51 - 90 kW	45,7%	48,3%	49,2%
91 - 130 kW	34,5%	32,3%	31,0%
131 - and more	12,9%	10,9%	8,9%

Comments:

a) up to 50 kW

- Trend: Downsizing does not mean necessarily performance reduction.
- No idea.
- ? Don't kno.
- The average performance will rather increase.

- *Electrified propulsion needs another kW-class than ICEs – not comparable!*
- *Progress will go in the direction of hybridisation and new fuels, but not on the costs of peak performance.*

b) 51 - 90 kW

- An increase may be expected due to reduction of driving resistances (weight, cross-sectional area, drag coefficient).
- This will continue to be the largest segment.
- Such a detailed prediction is reading in coffee grounds.

c) 91 - 130 kW

-/-

[320] Kba statistics on new registrations according to motorisation 2008: http://www.kba.de

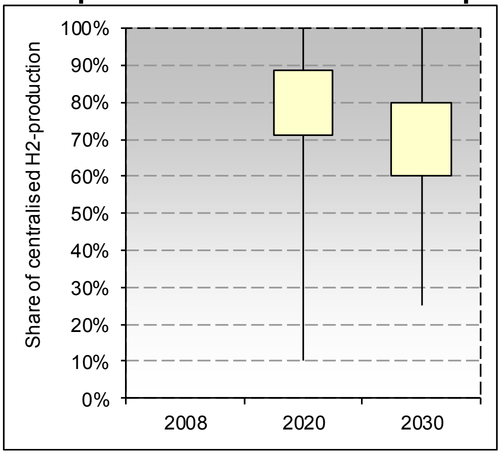
d) 131 - and more

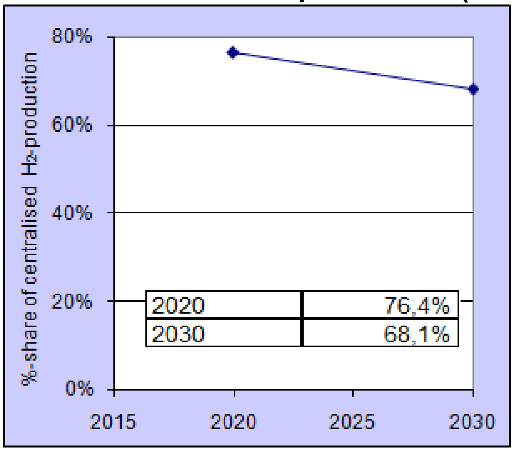
- Relatively low structural change.
- Including vehicles which reach an increased performance using short-term electrical boosting.
- High level of motorisation will sustain stable.

- *Coffee grounds.*

Q13: In Germany hydrogen fuel will be produced de-/centrally by 2030

Boxplots for 2020/2030 / Development of share of centralised H_2-production (mean)





Comments:

a) Centralised in large plants

- No estimation possible; no Business Case.
- 2020: Probably from fossil fuel, but some large wind farm generation; 2030: more from large renewable energy installations.
- In small amounts from processes, which are not specific fuel production processes, but are operated for other processes, e.g. for energy purposes.
- (If decentralised = local at the filling station).
- Decentralised is too expensive.
- Guess only H_2 for transport, not including existing industrial production?
- I am missing data – only estimation.
- Don't really know where German policy on H_2 stands today.

- *I agree partly with the majority*.
- *Economy of scale will be necessary as I don't think on-site conversion stands a chance economically. Mother-daughter stations will be the future*.

b) Decentralised in small distributed plants

- Electrolysis installations in situ at service stations.
- No estimation possible; no Business Case.
- Decentralised plants are cheaper for the use of excess wind energy.

- *The footprint of the conversion system plus fuelling station is WAY too large for normal urban applications.*

Q14: In Germany hydrogen fuel will be produced from / by ... by 2030

Comments:

a) Natural gas by reforming

- Large plants.
- The path leads away from fossil fuels.

- *Also with CCS.*

Median from single answers:

Question	a) Natural gas by reforming	b) Electrolysis using conventional national electricity mix	c) Electrolysis using renew. electricity f. wind energy or photovolt. being at the same time an energy storage medium	d) Chemical processses as a residue	f) Biomass by gasification or liquid reforming	h) Thermo-chemical processes (above 1.700 °C water vapour dissociates to H_2 and O_2
Median	4	3	5	3.5	3	2
Text in clear	Important	Neutral	Very important	Neutral	Neutral	Low importance

b) Electrolysis using conventional national electricity mix

- Important during transition to C while proving technology.

- *Incl. RECS*[321].

c) Electrolysis using renewable electricity from wind or solar energy being, at the same time, an energy storage medium

- Ultimate goal.
- Also an option for the use of fluctuating renewable wind electricity.
- Only useful if excess renewable energy from wind is available.
- Use of excess wind energy! The volume of excess energy depends on the overall power plant structure.

- *Direct connection between wind park and H_2-production.*
- *It is also important that H_2 is produced in this way. Unfortunately, a) and b) will continue to dominate in 20 years.*
- *Renewable electricity is the important panacea but once it's in the grid it can't be identified as 'renewable' except with the use of credits. If renewable electricity is successful in the long term (and it likely will be) the concern will be mostly on the input side of the grid and no longer on the output side. People can say their H_2 is from renewable power, but who will know unless it's used off-site and off-the-grid.*

d) Residue from chemical processes

- Probably will continue to capture H_2 this way.
- Important during the transformation phase.
- Available amount of residues decreases due to process innovation.

- *I do not believe in both.*
- *Too expensive; not enough capacity.*

f) Gasification or liquid reforming of biomass

- But will compete with Bio-Fuels for bio-mass.

- *Too expensive and energy inefficient.*

g) Others, please specify

- Thermo chemical process "Desertec".
- Coal + CCS.

New) Electrolysis using electricity from coal power plants in combination with CCS

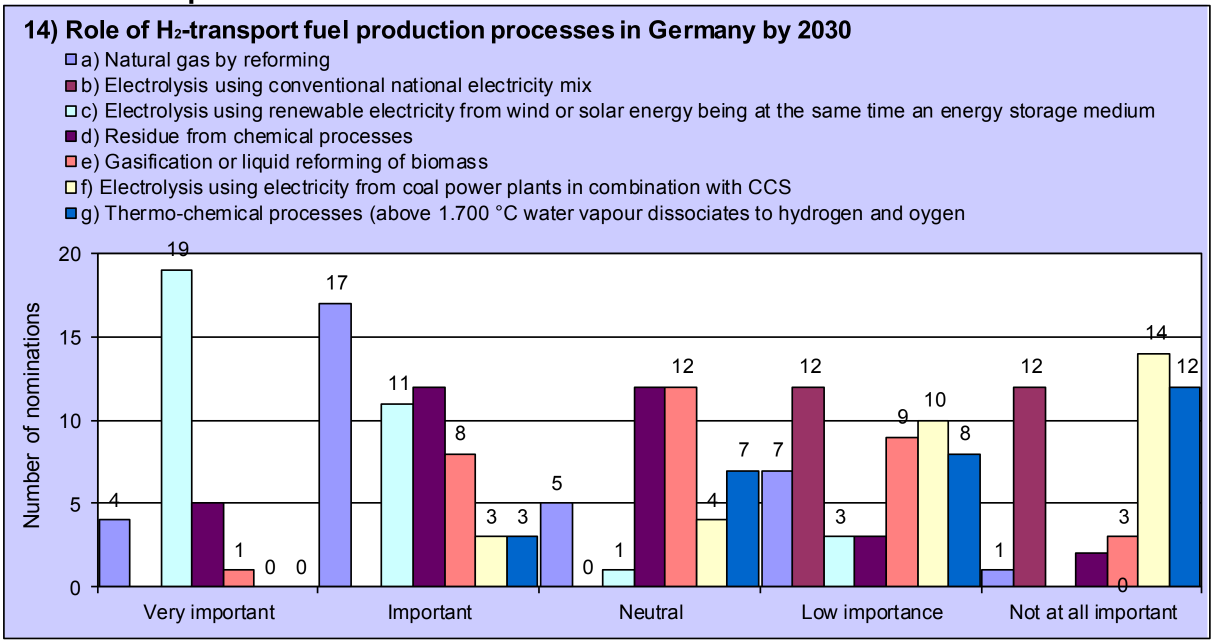
- *CCS is difficult to explain (or not at all)to the population.*

New) Thermo-chemical processes (above 1.700 °C water vapour dissociates to hydrogen and oxygen

- *Can't comment.*
- *For example, solar thermo processes (DESERTEC).*

[321] "Renewable Energy Certificates System": Certification system for electricity from renewable sources.

Distribution plot:



Q15: Future role of biofuels in Germany (by 2030)

Comments:

a) Pure use of biodiesel

- Already today it is out of the race due to emission discussion (suitable for particle filters).

b) Use of ethanol E85

- You mean use of 'pure' ethanol, as in 100% or what the market considers as E-85, 85% eth/15% gasoline (for luminosity)?

c) Blending of biodiesel to diesel

- -/-

d) Blending of ethanol to petrol

- -/-

e) Blending of biogas to natural gas

- -/-

f) Use of 2nd generation biofuels (BTL)

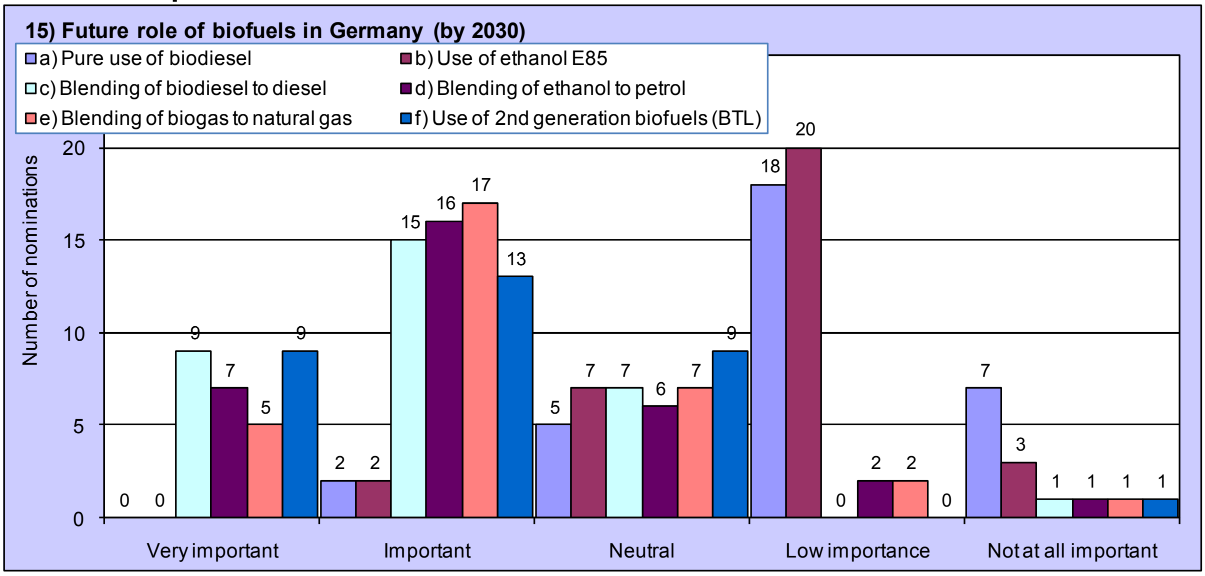
- Including hydrogenation of bio oils from refinery processes. However, CTL - Coal to Liquid - and GTL - Gas to Liquid – processes do not use agricultural or forest originated produced resources.
- For long distance transports and aviation.
- Only BTL is 2nd generation biofuel.

- *Maturing of technology is delayed.*

Median from single answers:

Question	a) Pure use of biodiesel	b) Use of ethanol E85 (mix. of 85% eth./15% gasoline)	c) Admixture of biodiesel to diesel	d) Admixture of ethanol to gasoline	e) Admixture of biogas to natural gas	f) Use of second generation biofuels
Median	2	2	4	4	4	4
Text in clear	Low importance	Low importance	Important	Important	Important	Important

Distribution plot:



Period within which the event / development will first have occurred

Q16: Peak Oil is reached

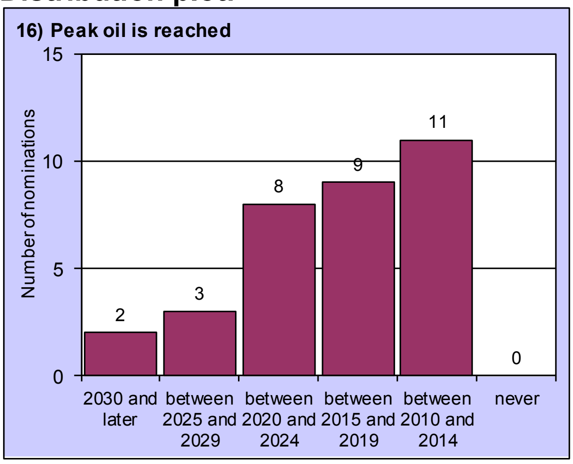
Median from single answers:

Median	2	Text in clear	between 2015 and 2019

Comments:

- We evaluate that the peak has already happened.
- The available oil resources are less of a problem than the limited oil production capacity.

Distribution plot:



- I cannot give an answer, I think, that the 'peak' will show as a long plateau.
- No reliable information available, national and international oil companies without a statement.
- No evaluation.
- It is not important if it already had happened or will come soon, is less decisive.

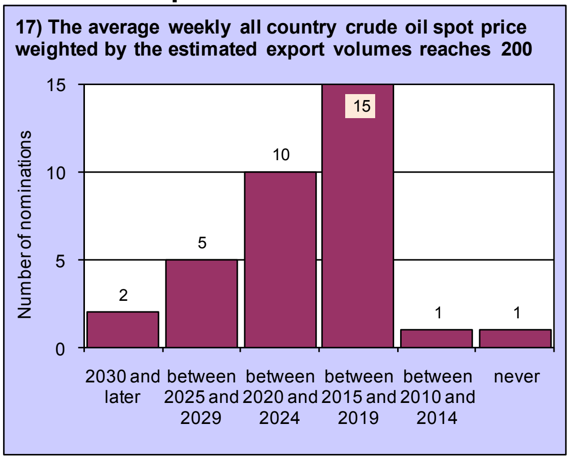
- *Replacement by "non conventional oil".*
- *Has been reached in 2006.*

Q17: The average weekly all countries crude oil spot price weighted by estimated export volume reaches 200 US$ per barrel

Median from single answers:

Median	3	Text in clear	between 2020 and 2024

Distribution plot:



Comments:

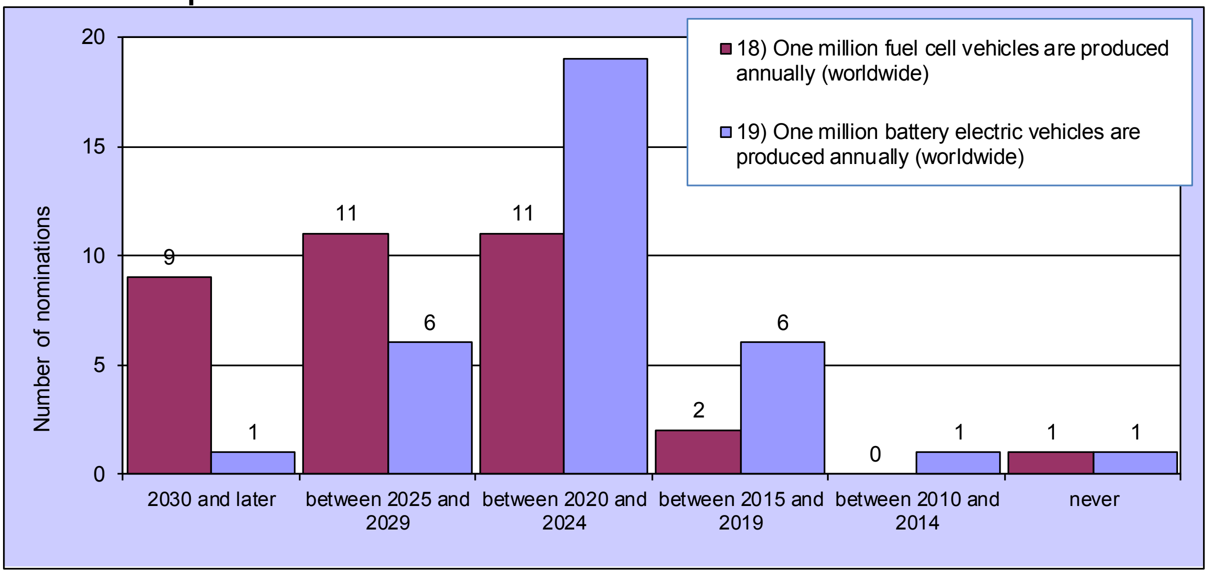
- If the oil price achieves such values permanently, other energy forms will become competitive; the oil producer will take care to ensure their supplies and will not cross the "magic price line". The level of this line is not known, a search process takes place.
- No estimation.
- If the resources achieve an end, prices will inevitably increase. In the case of war, which will hopefully never happen, prices will increase even faster.
- A high volatility of the oil price could be expected due to speculation and economic factors.
- Trend increasing, but due to the crisis the global amount of money increased strongly.
- *In 2010 monetary value*.

Q18: One million fuel cell cars are produced annually *(at least 4 wheels, no wheel chairs etc.)*

Median from single answers:

Median	4	Text in clear	between 2025 and 2029

Distribution plot:



Comments:

- Globally.
- Only if somewhere in the world a zero emission regulation such as in California is put in force by the government. This would lead to a significant loss of wealth in these countries. I do not believe in this option.
- Globally, not Germany only.

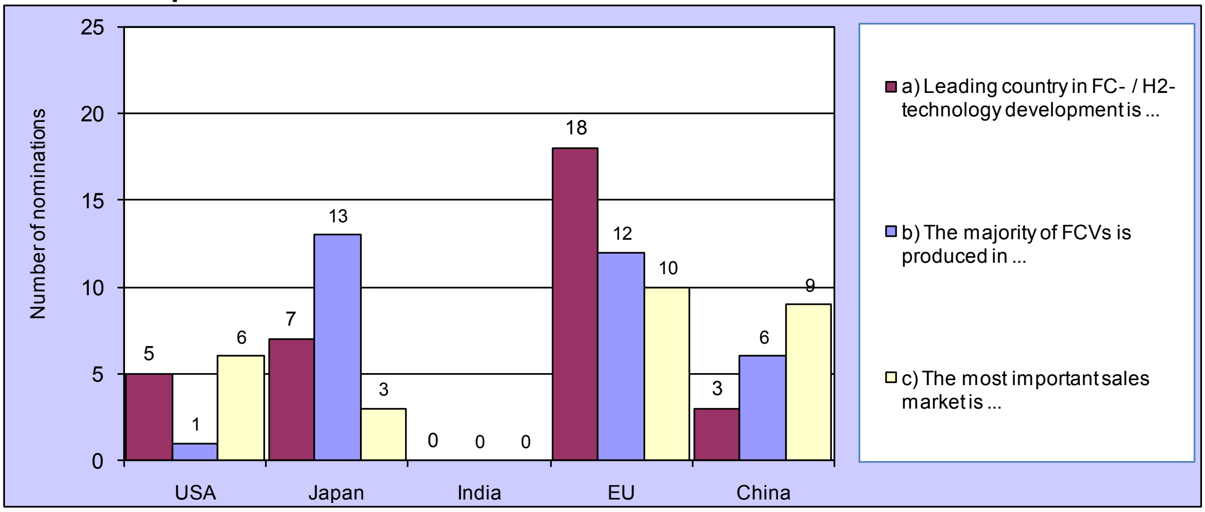
a) Leading country in FC- / H_2-technology development is ...

- In 2030. This is difficult - probably put my money on the Japanese - but would say they are all equal at the moment.
- Do not forget Korea.
- Neatly followed by Germany.
- FCs will be rare applications in vehicles, thus there is not much sense in answering this question. This is different for special applications in the military, aviation or space sector. If there are larger

amounts of H_2 from the management of fluctuating primary energy sources, stationary niche applications will appear.

- 2020?
- China has the most patent applications in the development sector.

Distribution plots:



b) The majority of FCVs is produced in ...

- In 2030/2020?

c) The most important sales market is ...

- In 2030: Mainly because they are rich and are more likely to afford them.
- 2020?
- There is no market yet, but it will be China, because a lot of money is available and the prestige thinking is (still) very high.

Q19 One million battery electric cars are produced annually *(at least 4 wheels, no wheel chairs etc.)*

Median from single answers:

Median	3	Text in clear	between 2020 and 2024

See graphics under question 18.

Comments:

- Globally.
- What kind of vehicles? Incl. motorised bicycles? If cars are meant, see marks set, this is equivalent to 1% of the global production.
- BEVs needs an intelligent management of the networks of renewable energies. This will not be realised, thus also plug-in-vehicles will remain a niche application. The answer related to plug-in and not to hybridisation.
- If Germany is meant.
- Including single track vehicles.
- See question 9 [Problem of origin of resources for production of storage system].

a) Leading country in BEV-technology development is ...

- In 2030 2020?
- Without Plug-in Hybrids.
- Co-operations are globally, synergies between the OEMs.
- Including single track vehicles.

b) The majority of the BEVs is produced in ...

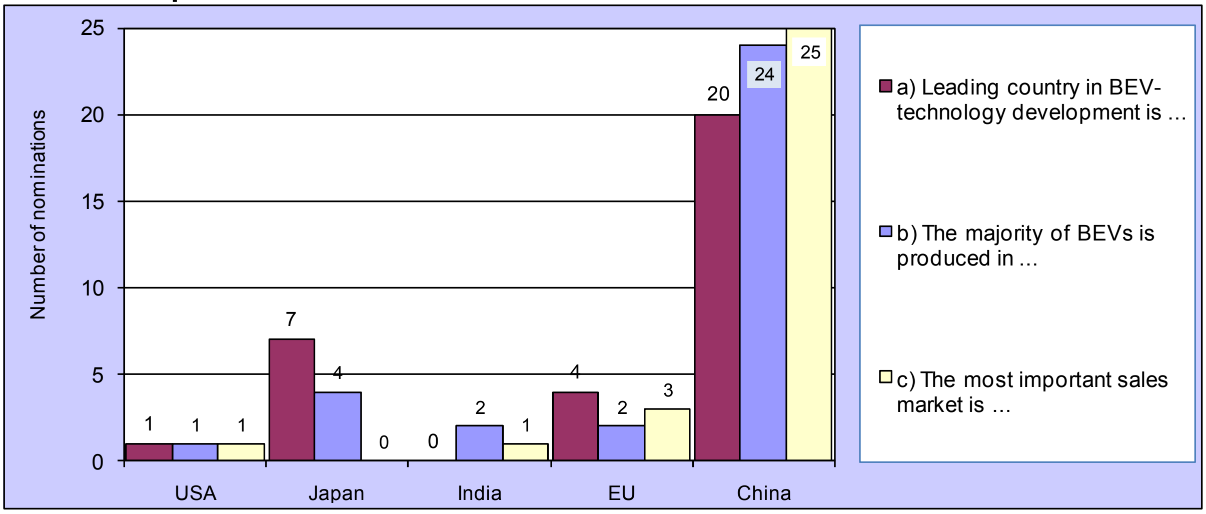
- In 2030 so-called Neighbourhood Electric Vehicles; ca. 5.000 E/a.

- 2020?
- Including single track vehicles.

c) The most important BEV sales market is ...

- In 2030 - This is because these countries have an imperative to clean up the air in their cities - and battery electric cars are most likely to be available for short range city driving in the medium term.
- 2020?
- If it becomes reality ...
- Including single track vehicles.
- Where else, they make a quarter of the global population?

Distribution plot:



Q20: The following new technologies are maturely developed

Median from single answers:

Question	a) Hybridisation of vehicles with spark ignition engine	b) Hybridisation of vehicles with compres. ignition engine	c) Heavy duty natural gas compression ignition engine	d) Spark-ignition-engine operated by a H_2-CH_4 blend
Median	2	2	3	2.5
Text in clear	between 2015 and 2019	between 2015 and 2019	between 2020 and 2024	2019/2020

Comments:

a) Hybridisation of vehicles with spark ignition engine

- Definition by % maturity for all technologies listed is (?) 10% market share (my definition).
- Hybridisation of the ICE happens in parallel.
- *"What is" "mature"? More precisely "most of the saving potential realised and technology has reached a point at the learning curve at costs similar to current leading technology vehicles."*
- *If you mean 'developed' then yes, the technologies will exist for commercial markets. If maturity is defined by % market penetration, that is a different answer.*

b) Hybridisation of vehicles with compression ignition engine

- However, too expensive.
- *See above ["What is mature?"]*

c) Heavy duty natural gas compression ignition engine

- ??
- No idea.
- Cannot evaluate priorities at the OEMs.
- No evaluation.

- Compression ignition must be dual fuel.

d) Spark-ignition-engine operated by a hydrogen-natural gas blend

- ??
- However, where is the benefit.
- Cannot evaluate the priorities at the OEMs.
- No evaluation.

- *Do not think that this is an option with potential..*
- *Technology is essential the same; H_2-CH_4 blends will never be popular over CH_4 alone.*

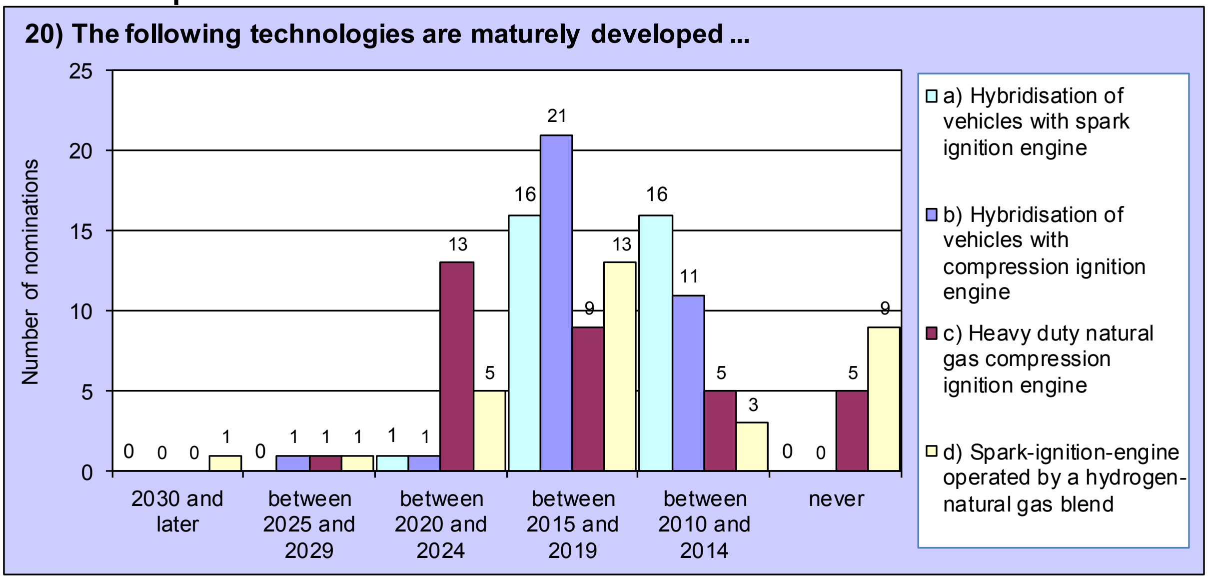
e) Others, please specify

- FC buses.
- Pure electric propulsion with storage.
- Drive torque based, integrated management of ICEs, electrical machines and storages, automatic gears, exhaust turbocharger, waste heat recovery.
- The development will never stop: The ICE has been improved over 100 years.
- HD natural gas spark ignited engine.
- HCCI / Diesel – spark ignition ICE.

f) Others, please specify

- -/-

Distribution plot:

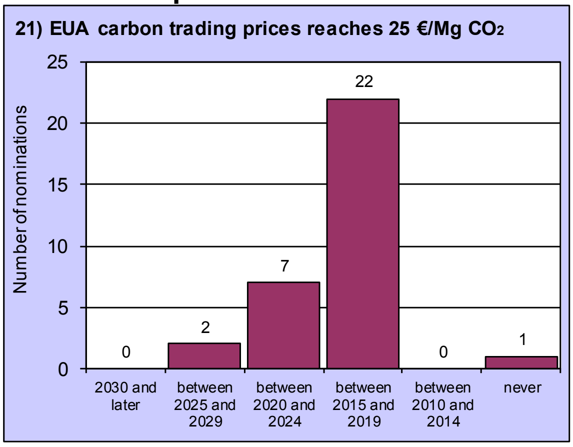


Q21: Carbon trading costs reaches 25 €/Mg CO_2 (assumption: including only current group of emitters)

Median from single answers:

Median	2	Text in clear	Between 2015 and 2019

Distribution plot:



Comments:

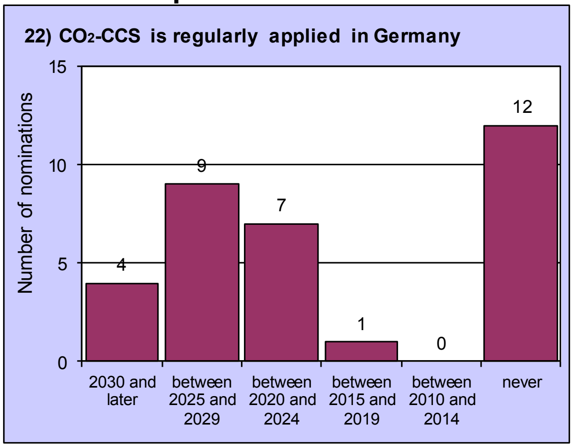
- This will depend on the design of the next phase of the EU-emission trading, in particular which emitters will be added to the emitters (stationary facilities with certain specifications). Currently, neither road transport, nor aviation or shipping are included; rail-bound transport means are only included indirectly through the inclusion of the power plants.
- The emission trading is based on the reduction of the certificates and the respective related optimisation of the processes. However, before the price would increase significantly, becoming a real cost factor, production would be relocated or optimisation potentials would be used, thus no real scarcity would occur.
- No answer.

Q22: CO_2 sequestration, capture & storage technology is regularly applied

Median from single answers:

Median	4[322]	Text in clear	Between 2025 and 2029 and 36% „never“

Distribution plot:



Comments:

- Will not work technically (on a higher level than a prototype) and will also not work during the next 50 years. By then, the technology will become superfluous because other alternative will have emerged.
- If the storage could be realised from a geological/ technical point of view.
- No answer.
- Not on a large. meaningful scale. Country-by-country applications based on geological cons-traints, economics, and competing technologies.
- No acceptance from the population in (Germany).

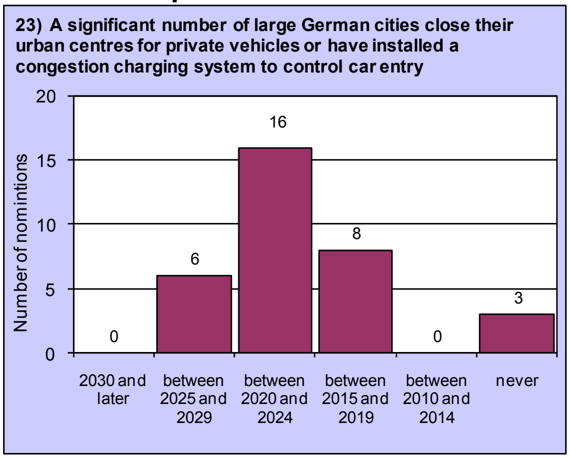
Q23: Significant number of large cities (at least 10) close their urban centres for private vehicles or have a toll system to control car entry

Median from single answers:

Median	3	Text in clear	between 2020 and 2024

[322] Due to the large amount of answers saying „never“, they are not included in the evaluation oft he median but are depicted separately.

Distribution plot:



Comments:

- In the case of Germany. Other countries have other problems and solutions.
- No necessity, climate problems will never interfere in such a way into life-style, it will be rather ignored (re-election of the politicians).
- Assumption: Question relates to Germany.
- What do you mean 'control'? Congestion charge or prohibition? For purposes of this answer, I assume 'congestion charging' or related behavioural or pricing controls. Also, how many is 'significant'?
- *In the form of environmental zones it has already started!*

Q24: Green *party platform issues* dominate European politics, increasing the respective regulatory power

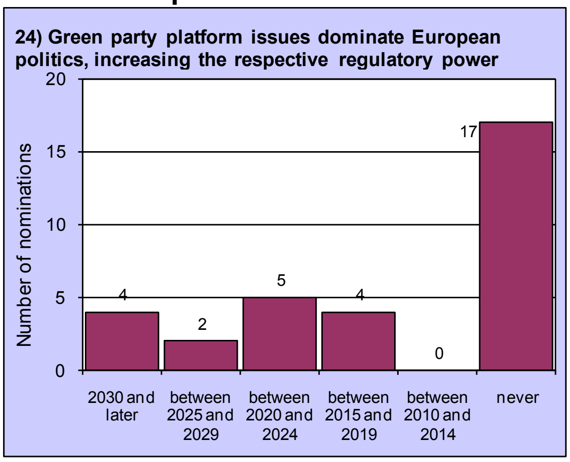
Median from single answers:

Median	6	Text in clear	never (53%)

Comments:

- No position on this topic.
- Not possible to be answered.
- ?
- A ‘one-topic’ party will not be successful in the long-term in a democratic system. You do not target the aspect that many green ideas are already common knowledge?
- Conservative parties will tend to support green topics and make green parties superfluous in the future. "Conventional" parties recognise the economic benefit of a ‘green’ policy and keep their electors. Green parties are too inconvenient for the consumer.
- ...however, the traditional parties will continue greening.

Distribution plot:



- No evaluation.
- All parties will become different shades of 'green' and the so-called 'green' parties will remain radical by comparison and, as such, usually a minority.
- Established parties will adapt if the “green movement” becomes stronger and thus ensure their power.
- *Green Topics increasingly receive higher energy and economical meaning, e.g. through the decrease of fossil energy imports.*

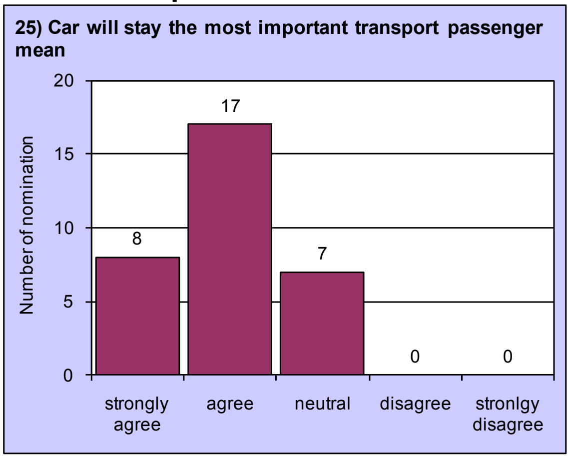
Please express your level of agreement (time horizon until 2030)

Q25: Car will stay the most important passenger transport means

Median from single answers:

Median	4	Text in clear	Agree

Distribution plot:

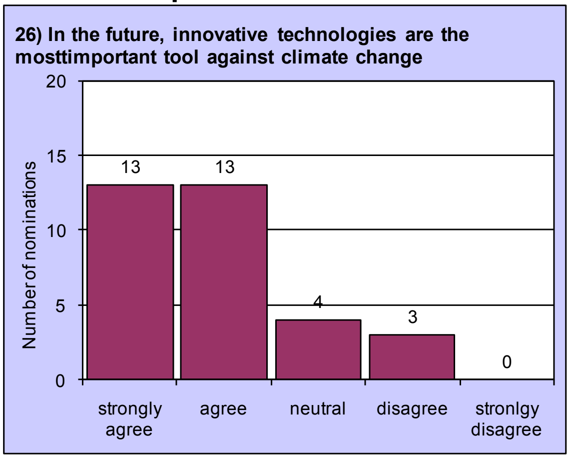


Comments:

- BE bicycle, public transport, mixture and diversity.
- Relates to the circumstance, rather not in urban areas but in rural areas.
- 1) urban areas/2 in rural areas.
- *As in the first round: Differs for urban (x1) and rural areas (x2)!*

Q26: In the future innovative technologies are the most important tool against climate change

Distribution plot:



Median from single answers:

Median	4	Text in clear	Agree

Comments:

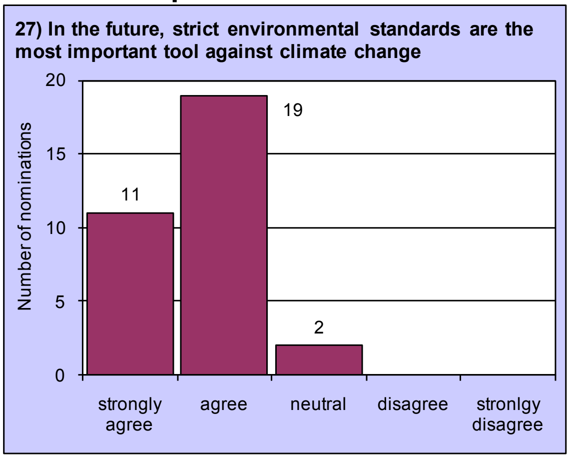
- As long as it is used increasingly for savings.
- Energy saving, change in behaviour.
- Change in behaviour is more efficient and cheaper with the same potential.
- Innovations are driven by stronger regulation.

Q27: In the future strict governmental standards (including all rise in costs of CO_2-emissions) are the most important tool against climate change

Median from single answers:

Median	4	Text in clear	Agree

Distribution plot:



Comments:

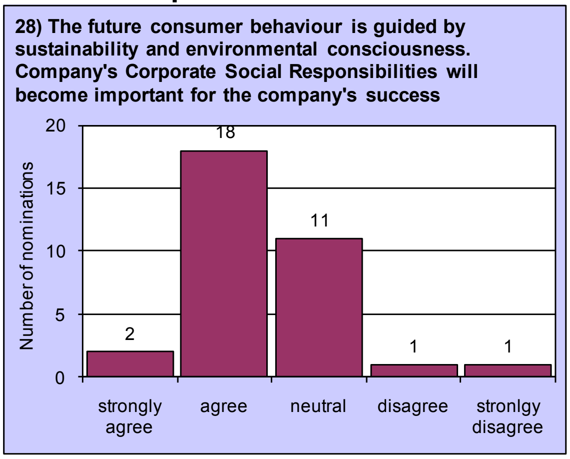
- Understanding seems to be unrealistic.
- Standards or mandates??? If mandates then agreement.
- If the politician make up their mind finally to implement them.
- Only changed Mindset from citizens and voluntary restrictions of the individual freedom will result in changed mobility behaviour. Mostly, financial thumbscrews have this effect.
- *Consumer mostly reacts to this or to price increases!*

Q29: In the future consumer behaviour is guided by sustainability and environmental consciousness. Company's Corporate Social Responsibilities will become important for company's success

Median from single answers:

Median	4	Text in clear	Agree

Distribution plot:

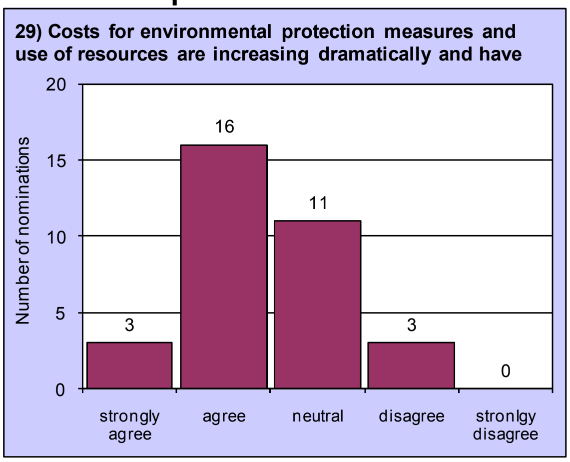


Comments:

- Social responsibility and the availability of sustainability strategies are already decisive factors for the evaluation of companies listed on a stock exchange and have a positive influence on the stock price.
- As always: it depends …
- Only when and if no limitations have to be feared. Sustainability/environmental protection are no guiding principles, but are lived if it suits.
- The consumer is orientated towards the price – at least for 90%. There is no reason to hope that this may change. Second part of the sentence is ok!

Q30: Costs of environmental protection measures and use of resources are increasing dramatically and have an increasingly negative effect on companies' profits

Distribution plot:



Median from single answers:

Median	4	Text in clear	Agree

Comments:

- It is also possible to earn money with environmental protection.
- See above, the politicians will not dare to force the polluter to pay for the external costs; the largest part will have to be paid by society.
- *I think the industry will know how to avoid a too strong impairment.*

Q30: Customers are ready to pay a premium for "green" products and services of up to 20%

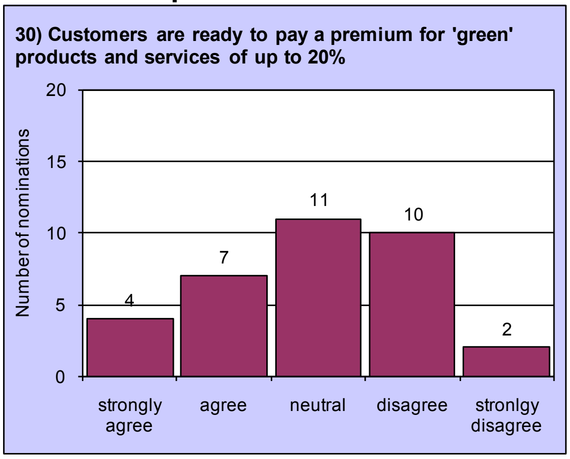
Median from single answers:

Median	3	Text in clear	Neutral

Comments:

- The readiness to pay is very low, only if there is a respective benefit, e.g. exception from the city toll.
- Depends on the basic price (20% of 1€ is different from 20% of 20.000€) and the respective marketing strategies.
- All recent attempts of the industry to sell eco-vehicles with premium price failed (VW Lupo 3l; Audi A2 TDI/ Audi Duo etc. etc.).In Germany with suitable marketing.

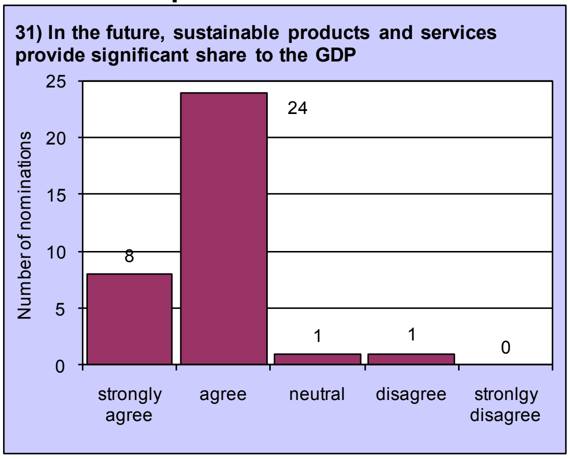
Distribution plot:



- Consumers delegate responsibility to the industry and are – in contradiction to respective polls – not ready to accept higher costs.
- A large percentage is ready in polls, but if it comes to implementation, only a few remain.
- *I think, the pressure (has to?) emanate(s) from the consumers, not from the industry.*
- *Acceptance depends heavily on how the income is used and how transparent this use is.*

Q31: In the future sustainable products and services provide significant share to the national GDP

Distribution plot:



Median from single answers:

Median	4	Text in clear	Agree

Comments:

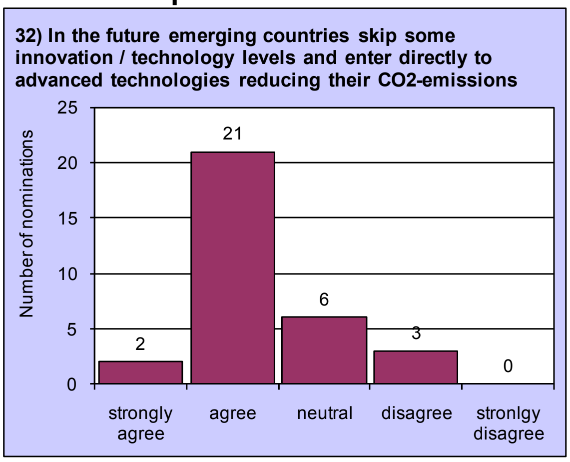
- What is this? Is a windmill sustainable? Or a combined-cycle gas turbine plant with> 60 % efficiency? How do you measure sustainability?
- Again, what's significant?
- If Germany were a global champion …..

Q32: Emerging countries undergo change in consciousness and policy supporting environmental and climate change measures

Median from single answers:

Median	4	Text in clear	Agree

Distribution plot:

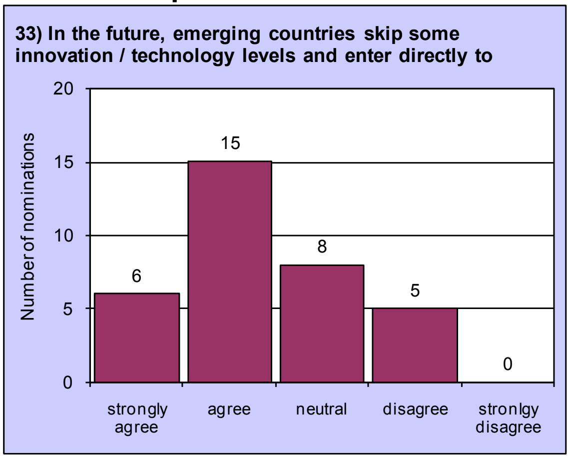


Comments:

- No change in awareness, but linking of development aid and environmental protection will give momentum (industrialised countries buy a clean consciousness through good environmental conditions for providing support to emerging and developing countries).
- Do not have good data.

Q33: In the future emerging economies skip some innovation/technology levels and enter directly to advanced technologies reducing their CO_2-emissions

Distribution plot:



Median from single answers:

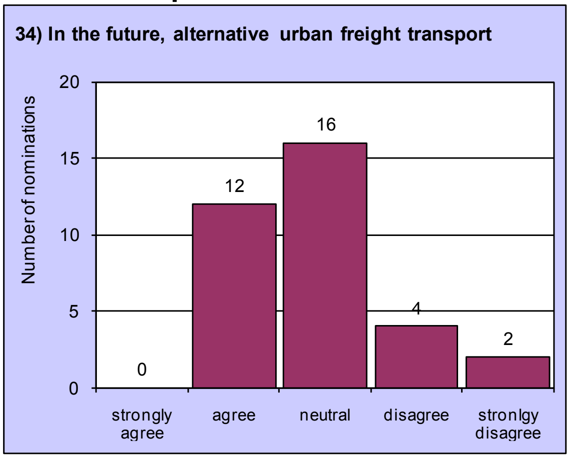
Median	4	Text in clear	Agree

Comments:

- See China, but not only due to environmental policy, but due to striving for power.
- Not for this reason, but no reasonable human being would use the technology of the day before yesterday, if he could get the one from today (or tomorrow).
- The industrialised countries would have to support this.

Q34: In the future alternative urban freight transport systems are implemented, e.g. tube systems, distribution centres etc.

Distribution plot:



Median from single answers:

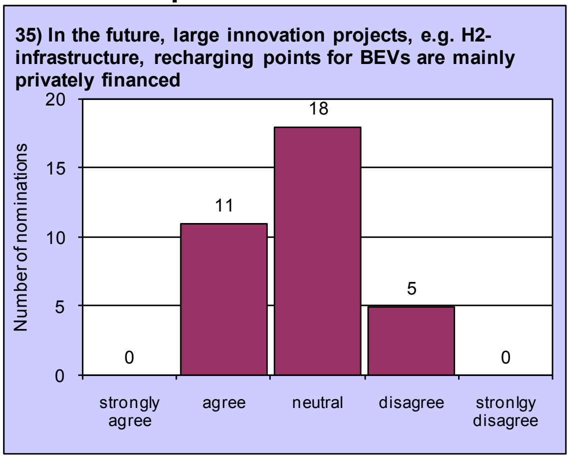
Median	3	Text in clear	Neutral

Comments:

- Distribution centres are already available. I am sceptical concerning pneumatic post.
- Zero Emission distribution vehicles.
- No answer.
- Distribution centres are already available.

Q35: In the future large infrastructure projects are mainly privately financed

Distribution plot:



Median from single answers:

Median	3	Text in clear	Neutral

Comments:

- Risk sharing necessary: Investments promise only long-term pay-back; public support, because public goals are followed.
- What do you mean? Streets; perhaps more filling/cahrging stations? H_2-infrastructure?
- Government will be significantly involved at least indirectly (guarantees, tax reductions, subsidies).
- The current moderate success in Germany (Warnow tunnel) speaks against. Without public funding etc. not thinkable, because the financial risks are too high (Transrapid!).
- *Direct financing perhaps private, but governmental if looking on it transparently (subsidies, tax, reductions etc.).*

- *Comprehensive private financing at decentralised use (e.g. charging points in the garage)*.

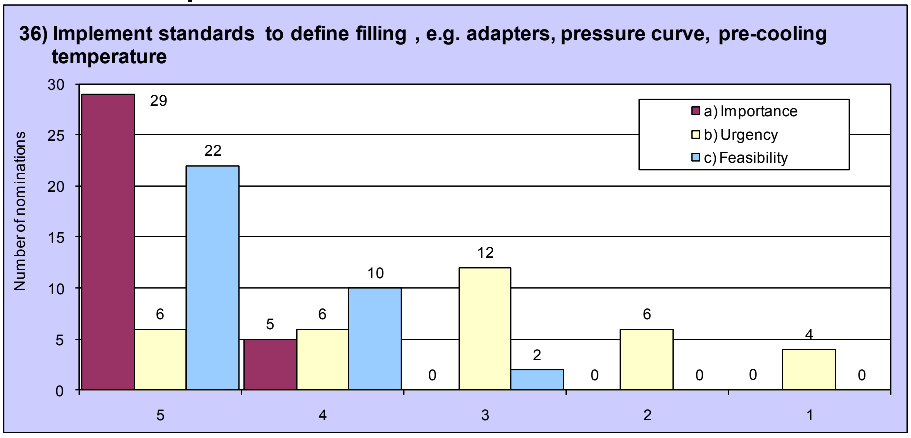
What specific short- to long-term actions could be undertaken to further promote the market introduction of hydrogen fuel?

Q37: Implement standards to define vehicle filling, e.g. adapter, pressure curve, pre-cooling temperature

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	5	3	5
Text in clear	Very important	Until 2015	Very feasible

Distribution plot:



Comments:

a) Importance

- The questions assume that the introduction of H_2 is seen as important. I would disagree. All answers are made with the provision of the meaningfulness of the strategic decision for hydrogen.
- Already being done at UN ECE level.

b) Urgency

- This is an ongoing process as technologies evolve.
- *Missing standards have already today an inhibiting effect.*

c) Feasibility

- < -40°C is also critical for cars in normal driving conditions.

Q37 Reliable mineral oil tax exemption for hydrogen as a fuel for at least 10 a

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	5	3	4
Text in clear	Very important	until 2015	Somewhat feasible

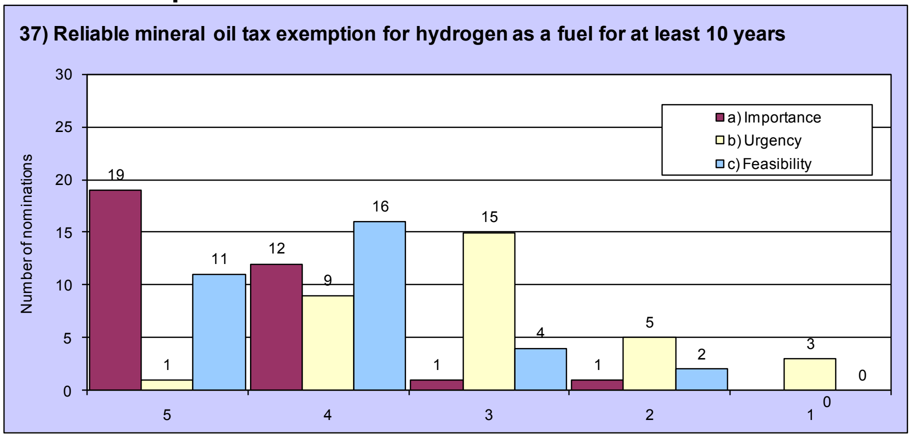
Comments:

a) Importance

- Considering the exorbitant technically caused costs for H_2, taxes are relatively an irrelevant cost factor.
- In total, a realistic cost/funding concept needs to be developed, because the H_2-cost will decrease heavily with large production. Approach e.g. Restriction of the H_2-production cost funding (but natural incentives for real cost reductions have to remain – the tax payer should not make the gas industry happy).

- Important if government and stakeholders put commercial H_2 as a priority, which I don't think they will. But it is important for the overall, long term success.
- *Reliable perspectives would be enough – this could be a linking to the mineral oil price (or fixed difference to the conventional fuels), see earlier questionnaire.*

Distribution plot:



b) Urgency

- Signalling effect, if anyone wants it really.
- Earlier on the level of projects, but no market.
- This would mean the exemption would be valid between 2020 and 2030.
- *Real market introduction programme, currently rather expedient, see question 38.*

c) Feasibility

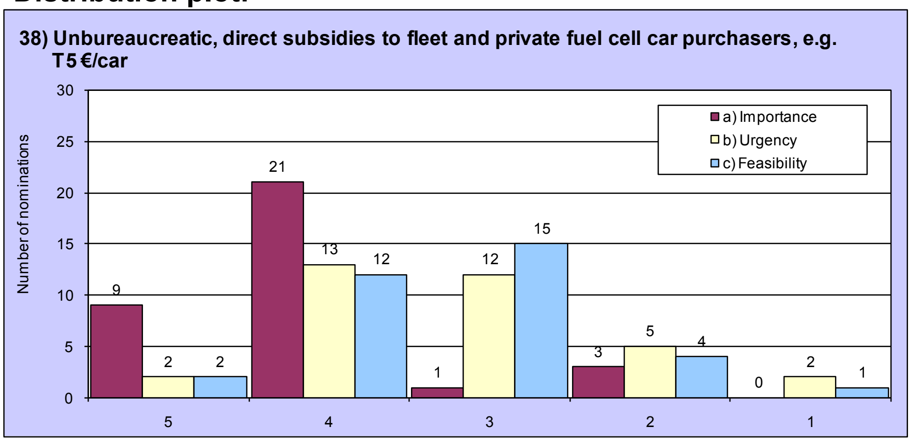
- As soon as H_2 gains significant market shares, a tax reduction is no longer possible.
- Solidarity throughout losses for the state, e.g. by an eco-cent on conventional fuels.
- It will be relevant only for a few number of vehicles, thus the financial minister will not (have to) be very reluctant.
- ... if it is really wanted.
- No assessment.

Q38 Non-bureaucratic direct subsidies to fleet and private fuel cell car purchasers, e.g. T5 €/car

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	3
Text in clear	Important	until 2015	neutral

Distribution plot:



a) Importance

- Only important during the next 10 a, afterwards no longer.
- 5.000 EUR will probably not be enough.
- Technology has to amortise or convince without; early customers will not have to rely on a subsidy, but will buy due to image reasons (marketing has to be right).
- Support to operators is the A and O for a successful market introduction, see wind energy in the 90-ties.
- Only for a limited number of vehicles (see scrapping bonus).
- See above, on political priority and 'will'.

- *See success of the scrapping bonus*.

b) Urgency

- Earlier it is relevant only for specialised fleets.
- Perhaps direct subsidies, if the wider market is to buy.

- *Currently rather fleet vehicles – subsidies have to development in parallel to the infrastructure.*

c) Feasibility

- In the medium - long term this should be entirely possible although maybe less necessary as price of oil goes up steeply.
- It will be relevant only for a few number of vehicles, thus the financial minister will not (have to) be very reluctant.
- It is already successfully implemented in the USA.
- No assessment.

- *European implementation, if the vehicles become available on the market*.

Q39: Public co-funding of hydrogen infrastructure beyond the first demonstration projects

Median from single answers:

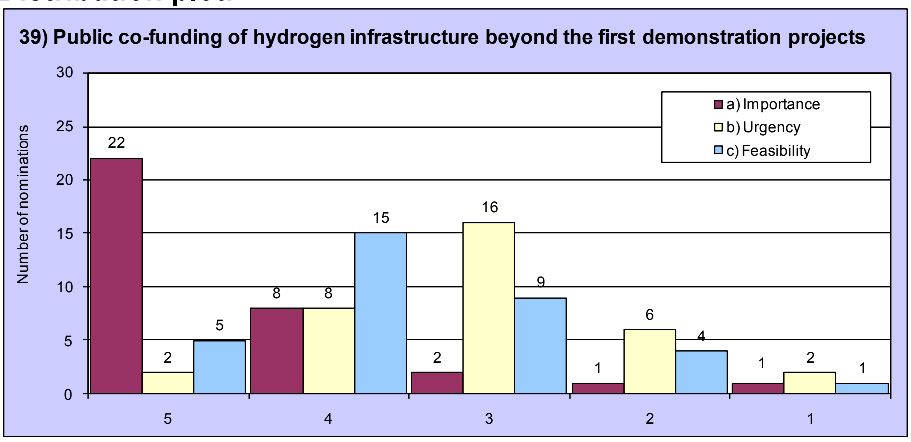
Question	a) Importance	b) Urgency	c) Feasibility
Median	5	3	4
Text in clear	Very important	until 2015	Somewhat feasible

a) Importance

- Should depend on the CO_2-balance of the production pathway.
- Do you mean financial support?
- If the technology is not economically efficient on its own, there will be no infrastructure.
- ... if the H_2-price is good, see question 37, and sales are stimulated, see question 38, the erection should be economical for the operator without further subsidies.

- *I partly agree with the majority, but think that primarily the H_2-price has to be good and that the vehicle sales have to be stimulated (see previous questionnaire).*

Distribution plot:



b) Urgency
- Depends on political priority. It's not happening without strong government support.
- Never.

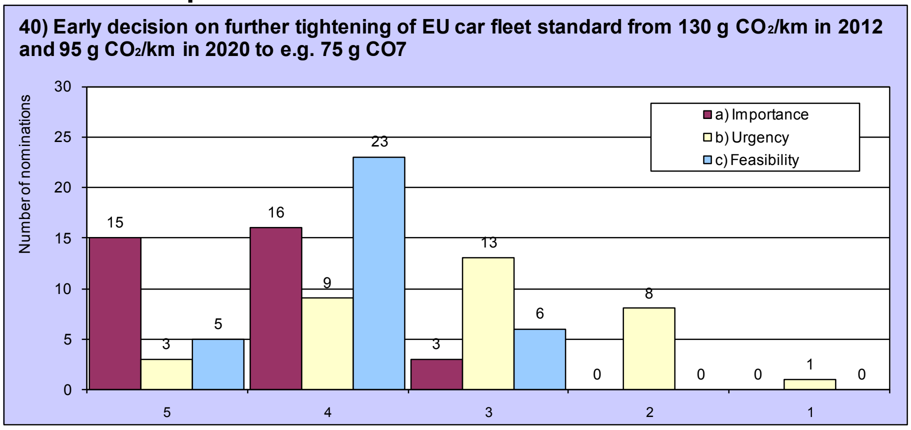
c) Feasibility
- Financing through the eco-cent?
- This could result in a waste of money mechanism and thus. has to be weighed in detail with the expected effects.

Q40: Early decision on further tightening of EU car fleet standard from 130 g CO_2/km in 2012 and 95 g CO_2/km in 2020 to e.g. 75 g CO_2/km in 2030

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

Distribution plot:



a) Importance
- In the EU the annual mileage and the specific consumption will probably decrease.
- Not relevant, image is more important than strict standards (OEMs have understood the market).
- ... if feasible.
- The industry receives clarification on development targets and is forced to act.
- *The targets need to be codified early, if compliance becomes feasible, is a different matter.*

b) Urgency
- No opinion.
- If the targets are still to be implemented, the industry will need about 15 years for a step by step implementation.
- ... if feasible.
- ???????????.
- *Now in the law: CO_2 and cars.*

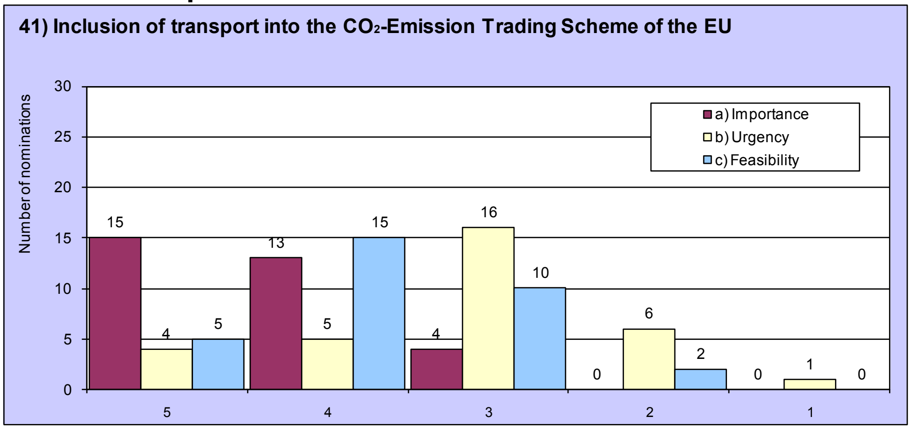
c) Feasibility
- From today's point of view only feasible, if the average vehicle fleet becomes lighter and smaller, this will probably have a negative impact on the passive vehicle safety.
- I cannot assess.
- ???????????
- Auto industry will stall and resist, as always.

Q41: Inclusion of transport into the CO_2-Emission Trading Scheme of the EU

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

Distribution plot:



a) Importance

- ???
- The inclusion has to follow the fuel production, not any fleet limit values or similar aspects.
- ...if feasible.
- There are other alternative policies.

b) Urgency

- No opinion.
- Earlier would be not realistic.
- ...if feasible.

c) Feasibility

- I would have thought that the measuring of carbon output etc. would be fairly hard to implement.
- If it is really wanted (probably problems with HDV transit countries in the EU).
- I cannot assess this, it seems not to be easy to realise.

Q42: Products and services are regularly labelled according to their CO_2-footprint

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

a) Importance

- There will probably be many practical assessment problems; concentration on the most important CO_2-producers is useful.

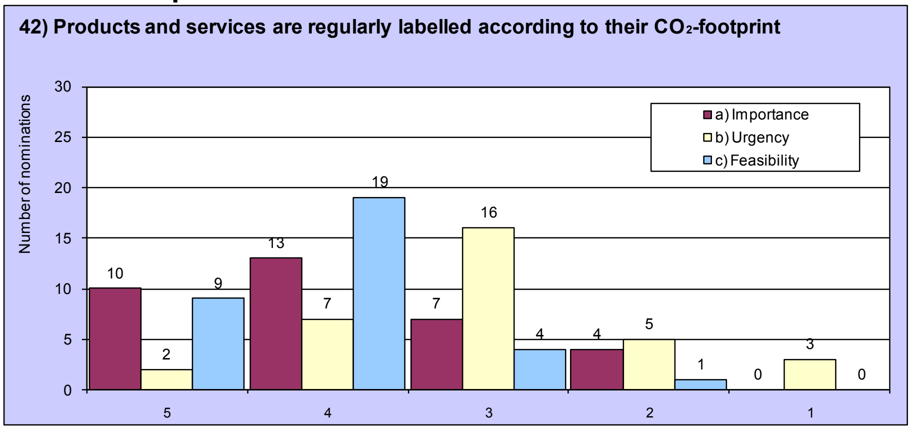
b) Urgency

- No opinion.
- Think this is on its way in Europe, but is not as important as some of the policy measures in my mind.
- See above [There will probably be many practical assessment problems; concentration on the most important CO_2-producers is useful].
- ????????.

c) Feasibility

- For cars: W-t-W or W-t-T?
- See above [There will probably be many practical assessment problems; concentration on the most important CO_2-producers is useful].
- ?????????.

Distribution plot:



Q43: International mandatory targets for further CO_2-reduction beyond 'Kyoto-agreement' are available and kept by nations

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	5	3	3
Text in clear	Very important	until 2015	neutral

a) Importance

- Kyoto will have no success because it is only paper work (paper tiger).

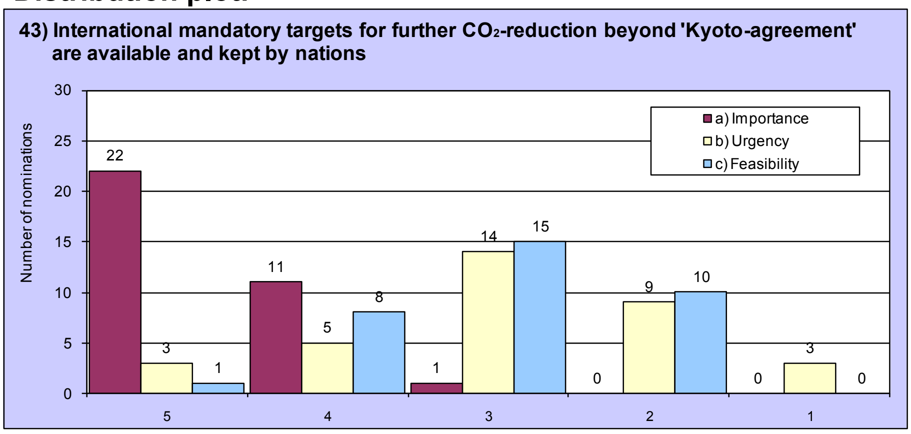
b) Urgency

- Even the 95 g will not be feasible earlier than 2020.
- *2: this seemed to be too optimistic*.

c) Feasibility

- Feel very pessimistic about this - really believe it could be the cause of major world conflict eventually.

Distribution plot:

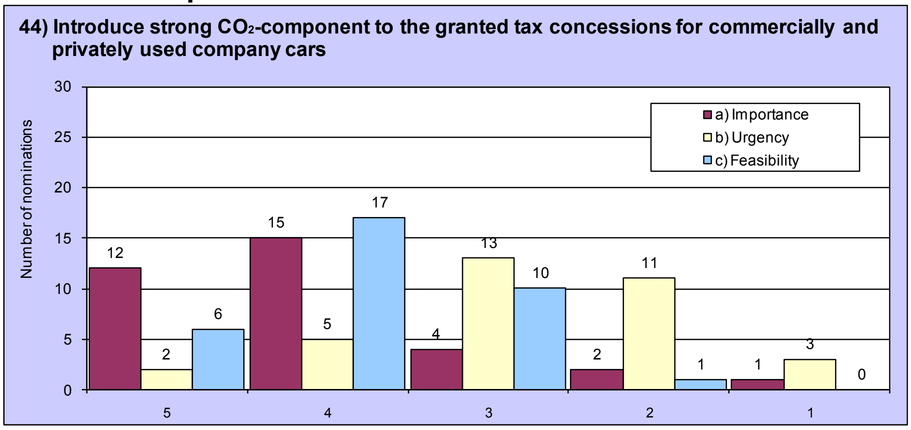


Q44: Introduce strong CO_2-component to the tax concessions granted for commercially and privately used company cars

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

Distribution plot:



a) Importance

- Starting with commercial vehicles is a great way to go.
- It would be better to “penalise” the CO_2-emmissions of the vehicle with a taxation of the fuel. No fuel consumption - no costs!

b) Urgency

- -/-

c) Feasibility

- Best: Link the tax deductibility of company cars to the max. CO_2-emissions (if higher, no deductibility).

Q45: Implement information platform for fuel cell vehicle users and purchasers comparable to German national "Erdgasinitiative"

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

a) Importance

- Not sure of the Erdgas Initiative, but if it has been done for that then it can be easily done for FC users and is important because it is a breakthrough technology.
- Sales handbook no – practical testing yes.
- I think it is not important to belong to a specialised club, but to make it clear that FCs are an alternative for the mass market.
- Something for freaks, verbal propaganda is more important.

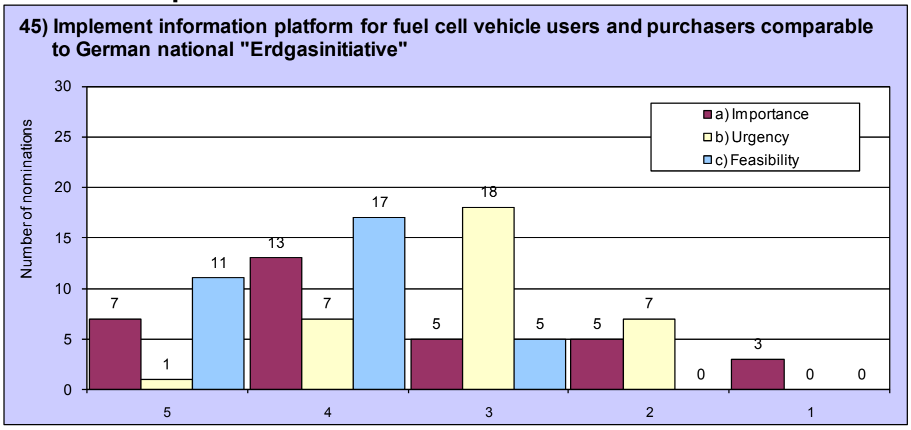
b) Urgency

- No opinion.
- Real market for private FCVs not before 2015.
- If the vehicles are available to the public.

c) Feasibility

- ... depends on the design.

Distribution plot:

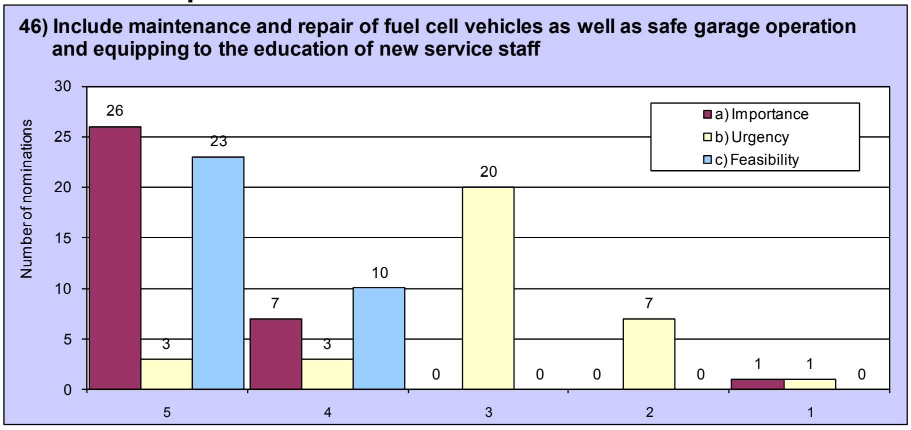


Q46 Include maintenance and repair of fuel cell vehicles as well as safe garage operation and equipping to the education of new service staff

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	5	3	5
Text in clear	Very important	until 2015	Very feasible

Distribution plot:



a) Importance

- This is a particularly important issue as the "lead time" for having sufficient and sufficiently trained technical and operating staff can be as long as 10 years.
- It does not work in another way. From my point of view, mobility will be sold, not vehicles in the future.
- Not only mechatronics, but also mechanical and electrical engineering.
- I interpret mechatronics as car mechanics.

- *Gas AND electricity*!

b) Urgency

- Start with education until 2015.
- Depends upon market penetration rates.
- If the vehicles are available to the public.

- *Long lead times of educational changes.*
- *Should start in 2015 to be effective from about 2018 onwards.*

c) Feasibility

- -/-

Q47: Train existing maintenance and repair personnel to service fuel cell vehicles

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	5	3	5
Text in clear	Very important	until 2015	Very feasible

a) Importance

- Same comment as above [This is a particularly important issue as the "lead time" for having sufficient and sufficiently trained technical and operating staff can be as long as 10 years.]
- The own garage staff not, but absolutely the staff of the manufacturers.

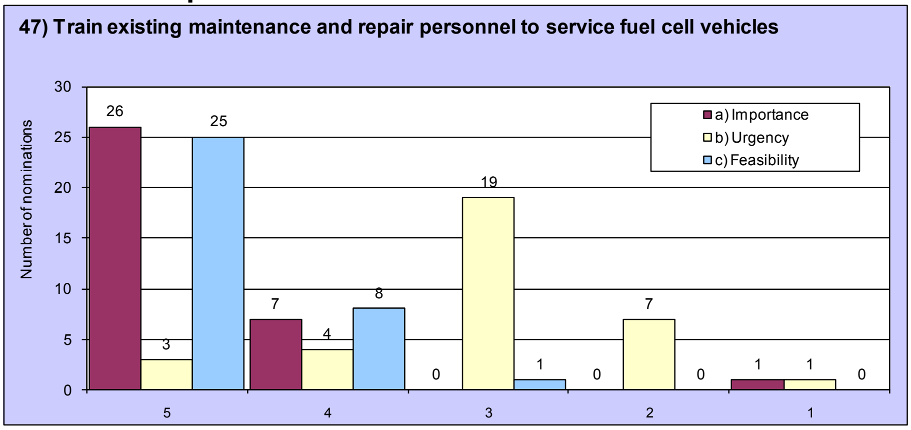
b) Urgency

- Start of education until 2015.
- See question 46 [If the vehicles are available to the public.].
- *May start then in question 46, because less lead time is necessary until it becomes effective.*

c) Feasibility

- -/-

Distribution plot:



Q48 Train sales personnel to better market fuel cell vehicles among conventional vehicles

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

a) Importance

- First, the technology needs to be more reliable and distributed.
- *I guess if OEM's need the pull of markets this is important*.

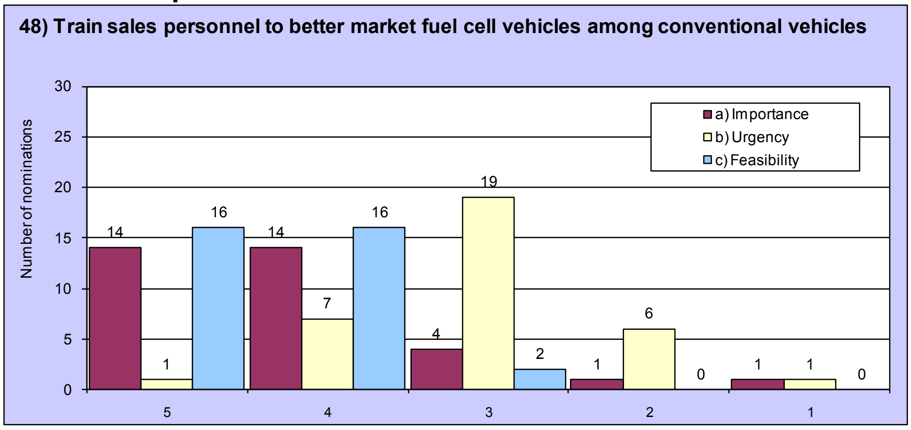
b) Urgency

- See question 46 [If the vehicles are available to the public.].

c) Feasibility

- -/-

Distribution plot:

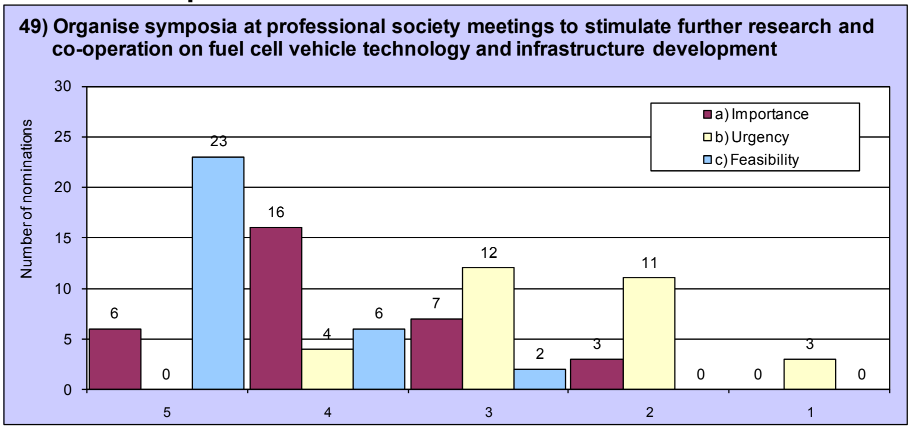


Q49: Organise symposia at professional society meetings to stimulate further research and co-operation on fuel cell vehicle technology and infrastructure development

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	5
Text in clear	Important	until 2015	Very feasible

Distribution plot:



a) Importance

- In my view there is a lot of this going on - what the H_2 world is not doing is going outside to the people who are less convinced.
- How many coals should otherwise be carried to Newcastle?
- *At the H_2FC annual Platform meeting they still have an incredible amount of financing, and everyone was complaining that governments aren't funding them enough.*

b) Urgency

- No opinion.
- Does already happen? International exchange on governmental level necessary!
- Regularly.
- Even if 2010 is nearly finished – it should start early to gain an effect for 2012 and later.

c) Feasibility

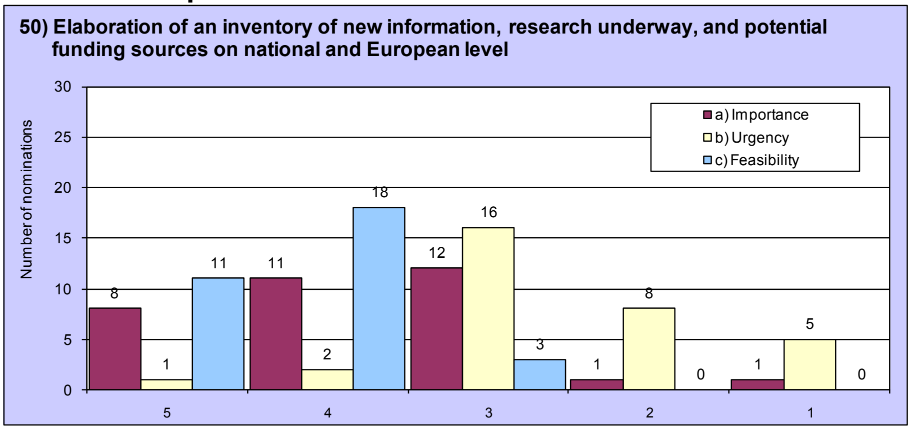
- -/-

Q50 Elaboration of an inventory of new information. research underway, and potential funding sources on national and European level

Median from single answers:

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

Distribution plot:



a) Importance

- .. I am not sure what already exists.
- ditto: [How many coals should otherwise be carried to Newcastle?].

b) Urgency

- No opinion.
- Think it has been/is already done.

- *Think this is probably already out there?*
- *The confusion on and the complexity of the support possibilities is one of the main disadvantage of the EU compared to Northern America.*

c) Feasibility

- Since 1986 the EU has spent some €1.02 billion on fuel cell and hydrogen development. Unbelievable!

Q51: Payment of an "H_2-Cent" - charged from each litre of gasoline or diesel sold - to the building-up of a hydrogen infrastructure

Question	a) Importance	b) Urgency	c) Feasibility
Median	3	3	2.5
Text in clear	neutral	until 2015	

a) Importance

- *Development money is important but I wonder about the practicality of this.*
- *Financial support always has to be seen critical, see coal cent.*
- *The introduction of such a drastic measure for only one technology is problematic, rather support to sustainability.*
- *As a replacement to the measure in question 39.*
- *This is a not a wise policy option to focus only on hydrogen fuel cell vehicles through fuel tax subsidization when there are so many more feasible alternative fuel vehicle options are available TODAY. Any subsidization through fuel taxation should be 'fuel neutral' to clean fuels or vehicles that achieve specified criteria.*
- *For this it would be necessary to see that H_2 would be the future of mobility!*

- *Reasonable for the use of all "renewable energy carriers" in the transport sector, a singular support to H_2 would create an H_2-acceptance problem ("H_2-compulsory levy").*

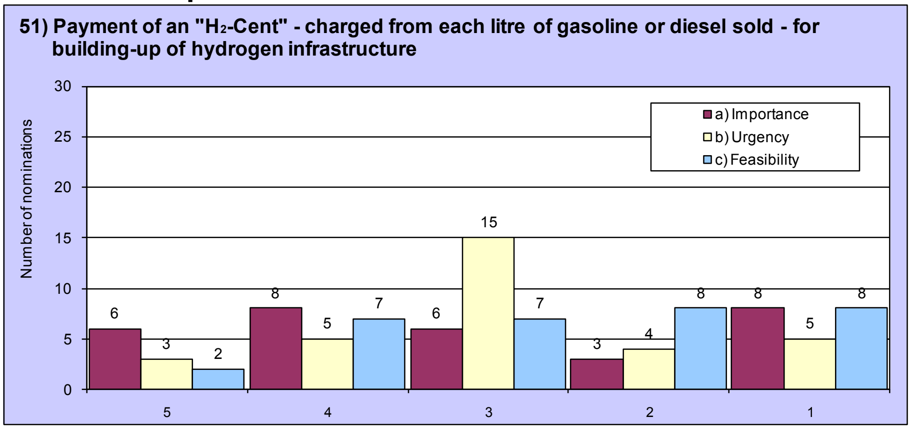
b) Urgency

- *As long as the future of the coal cent is not solved, this kind of levy should not be in focus.*
- *If so, then it would need to start early.*
- *The fuel industries would not stand for it.*

c) Feasibility

- *Acceptance is in question – electricity is already more expensive due to the photovoltaic.*
- *See above.*
- *Not in these economic times.*
- *Kind and transparency of use of the income would be very important for acceptance.*

Distribution plot:



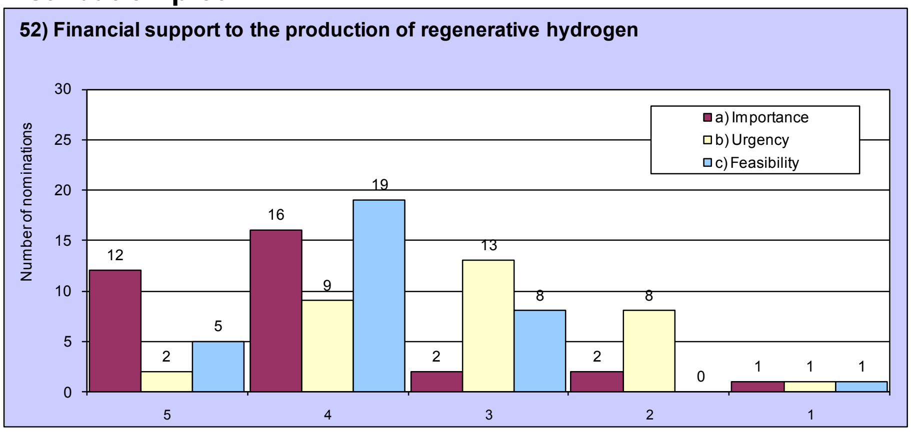
Q52: Financial support to the production of regenerative hydrogen

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	until 2015	Somewhat feasible

a) Importance

- *Support for a short transmission phase with decreasing tendency.*
- *See question 51.*
- *Reasonable for the use of all "renewable" energy pathways in the transport sector, a singular support to H_2 would create an H_2-acceptance problem ("H_2-compulsory levy").*

Distribution plot:



b) Urgency

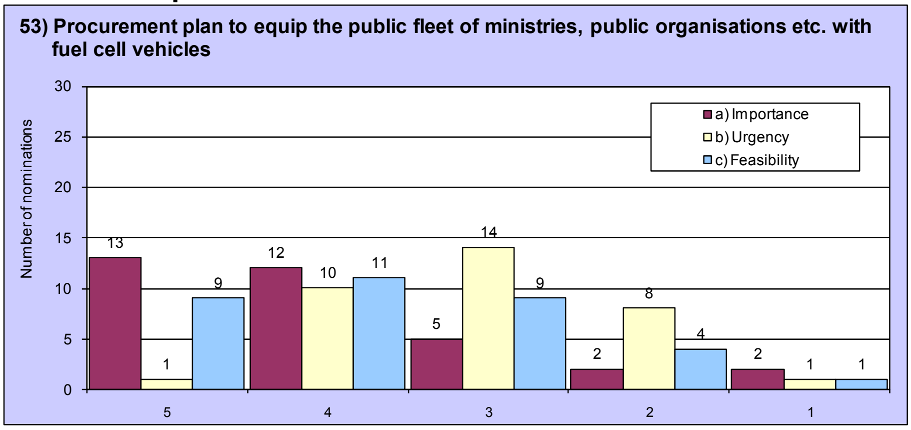
- *See question 51.*
- *Will become important if larger fleets start operation.*

c) Feasibility
- *Could be helpful in the beginning to avoid the danger of misallocation of funding programmes.*
- *See question 51.*
- *Question of the priority concerning the support of demand.*
- *Kind and transparency of use of the income would be very important for acceptance.*

Q53: Procurement plan to equip the public fleet of ministries, public organisations etc. with fuel cell vehicles

Question	a) Importance	b) Urgency	c) Feasibility
Median	4	3	4
Text in clear	Important	Until 2015	Somewhat feasible

Distribution plot:



a) Importance
- *Model and pioneer function.*
- *Classic, efficient measure (see US Army) – but in this case it could be difficult to include only one technology, perhaps it should be formulated more generally (CO_2-neutral, sustainable, etc.).*
- *Under the new Clean & Efficient Vehicle directive H_2FC vehicles won't make the cut…AT ALL.*

b) Urgency
- *-/-*

c) Feasibility
- *Good possibility to increase the production numbers quickly. Because administrations have large fleets, this would be also possible with an initially low infrastructure density.*
- *Great idea but very political…..certainly would provide a market.*
- *See above.*
- *Adequate vehicles are not available.*

New Ideas (only first questioning round)

New Idea #1:
- H_2 - Cent: A tax of 1 ct. is kept from each litre petrol or diesel sold; the tax is earmarked for the H_2-infrastructure erection.
- Take information on Hydrogen and Fuel Cell Futures to those who are less convinced and listen to and answer their concerns where possible. This will be part of the proposed CHIC project.
- Promotion of renewable H_2&FC like in the German EEG.
- Support to the introduction of the FC-technology (buses) in public transport: high level of perception, large emission reduction effect, fuelling infrastructure easy to install.
- Certify and publish the H_2-production chain, incl. energy balances.
- Municipalities need to receive more means for decision and financing (take municipal added value into account, the support of the municipality eases receiving of respective licenses).

- From our point of view a combination of political framework conditions (CO_2-standards), H_2-infrastructure and receiving number of vehicles (e.g. through direct tax support) to achieve a cost decrease.
- Introduction in non-vehicle FC-markets, to familiarise users, politics … and early start of value added chains.
- Immediate start of support to operators (20 years ago, this led to the very successful breakthrough of the wind energy use) – through growing demand and some initial help the H_2-infrastructure may grow.
- Use of bus lanes for H_2-vehicles, change all vehicles of the Bundestag and ministries, all buses of the DB, all vehicles of police, custom services etc.
- Hydrogen production in desert with solar energy, transport of large amounts over large distances on cryogenic ships.
- Show value chains, H_2 could be used not only as a fuel but also as a storage medium for renewable electricity.
- Figure out 'who' is the hydrogen industry and how the fuel delivery infrastructure will be financed and built.
- Improvement of the public relations work to improve the acceptance from the population and to reduce reservations and fears of the use of hydrogen fuel. (In this context, most citizens may remember the pictures of the Hindenburg accident in Lakehurst in 1937.)
- Benefits for low-emission vehicles, in particular in cities, this is also valid for BEVs.
- Creation of mechanisms for the allocation of H_2-fuel by sectors for transport in Europe: H_2 for cars (urban traffic, mid- and long distances) and commercial traffic (urban traffic), liquid biofuels for commercial transport on long distances.

New Idea #2:

- Clearly the production of 'clean' hydrogen and developing a distribution network for it must be a priority for an environmentally sustainable system.
- Lobby organisation for $regH_2$ together with other renewables interest groups.
- Not new: Exception from city toll, use of bus lanes etc.
- Depiction of costs of a possible infrastructure; how a future H_2-supply logistic could work, bringing FCV costs to the level of conventional vehicles.
- Transport sector should not be viewed separately, but as part of the overall economy (storage medium hydrogen, support or synergies with the stationary sector).
- Open discussion of the topic. School kids are better informed on the interrelations than I have been until the start of FC research.

New Idea #3:

- Targeting and shoring up political will remains a key task.
- New business models for FCVs.
- Not new: Change public fleets to H_2-vehicles.
- Let’s start with small series - about 100 vehicles in one region, see E-Smarts.
- Show that for such projects infrastructure, mobility, politics and communication need to cooperate and do it already.

8.9 References

Ackermann, Fran; Eden, Colin: Strategic Management of Stakeholders: Theory and Practice. In. Long Range Planning 44 (2011), p. 179-196

***ACEA**:* The automotive pocket guide 2011. Brussels. September 2011

ACEA: Highlights of the Annual Tax Guide 2013. Brussels 2013
Available at: http://www.acea.be/images/uploads/files/20130326_TaxGuide2013Highlights.pdf, Accessed: 14.03.2013

ADAC: Vehicle tests reports, Mercedes B-class, Toyota Prius
Available at: http://www.adac.de/_ext/itr/tests/autotest/at3855_mercedes_b_170/mercedes_-b_170.pdf; http://www.adac.de/_ext/itr/tests/Autotest/AT4790_Toyota_Prius_1_8_Hybrid/Toyota_-Prius_1_8_Hybrid.pdf; Accessed: 09.02.2014

AFCC, Automotive Fuel Cell Corporation: AFCC Research Needs Analysis for Generation 4 Vehicles. 2015
Available at: http://www.afcc-auto.com/wp-content/uploads/2015/06/CriticalResearchNeeds.pdf; Accessed: 05.11.2015

***AFCG, Alternative Fuels Contact Group**:* Market Development of Alternative Fuels - Report of the Alternative Fuels Contact Group. Brussels, December 2003
Available at: http://www.calpg.cz/VismoOnline_ActionScripts/File.aspx?id_org=600161&id_dokumenty=1172; Accessed: 23.02.2008

Air Liquide: Fortschritte beim Aufbau einer Wasserstoffinfrastruktur. In: Portal AL Ausgabe 7, 2009/2010

Air Liquide: Sicherheitsdatenblatt. Wasserstoff verdichtet. 28.08.2012
Available at: http://www.airliquide.de/gasekatalog/sdb/067A-DE-DE-Wasserstoff_verdichtet.pdf; Accessed: 12.04.2014

Albrecht, Uwe: Potenziale der Wind-Wasserstoff-Technologie in der Freien und Hansestadt Hamburg und in Schleswig-Holstein. Eine Untersuchung im Auftrag der Wasserstoffgesellschaft Hamburg e.V., der Freien und Hansestadt Hamburg, vertreten durch die Behörde für Stadtentwicklung und Umwelt, sowie des Landes Schleswig-Holstein, vertreten durch das Ministerium für Wissenschaft, Wirtschaft und Verkehr. Ludwig-Bölkow-Systemtechnik GmbH. September 2010

Alcock, J.L.; Shirvill, L.C.; Cracknell, R.F. (Shell): Compilation of existing safety data on hydrogen and comparative fuels. 2001
Available at: http://www.eihp.org/public/documents/CompilationExistingSafetyData_on_H2_and_-ComparativeFuels_S.pdf; Accessed: 12.02.2012

Angerer, G.; Marscheider-Weidemann, F.; Lüllmann, A.; Erdmann, L.; Scharp, M. Handke, V., Marwede, M.: Fraunhofer Institut für System- und Innovationsforschung ISI; Institut für Zukunftsstudien und Technologiebewertung IZT gGmbH: Schlussbericht Rohstoffe für Zukunftstechnologien. Einfluss des branchenspez. Rohstoffbedarfs in rohstoffintensiven Zukunftstechnologien auf die zukünftige Rohstoffnachfrage. Karlsruhe 15. Mai 2009
Available at: http://isi.fraunhofer.de/isi-wAssets/docs/n/de/publikationen/Schlussbericht_lang_-20090515_final.pdf, Accessed: 26.07.2014

Badenhop, Thomas: Brennstoffzellen in der Hausenergieversorgung. In: Töpler, Johannes; Lehmann, Jochen: Wasserstoff und Brennstoffzelle; Technologien und Marktperspektiven. Berlin 2013

Baker, Ryan; Zhang, Jiujun: Proton exchange membrane or polymer electrolyte membrane (PEM) fuel cells. In. Electrochemistery Encyclopedia. Vancouver, British Columbia, Canada, April, 2011
Available at: http://knowledge.electrochem.org/encycl/art-f04-fuel-cells-pem.htm; Accessed: 01.12.2012

Bakker, Sjoerd; Budde, Björn: Technological Hype and Disappointment: Lessons from the Hydrogen and Fuel Cell Case. In: Special Issue: Waiting Games: Innovation impasses in situations of high uncertainty. Technology Analysis & Strategic Management. Volume 24, Issue 6, 2012

Bakker, Sjoerd: The car industry and the blow-out of the hydrogen hype. Energy Policy (2010), doi:10.1016/j.enpol. 2010.07.019
Available at: http://www.academia.edu/205568/The_car_industry_and_the_blow-out_of_the_hydrogen_hype; Accessed: 01.08.2013

Bauer, Birgit: Image-Ranking 2011. In: Verkehrsrundschau 08/2011, p. 22

Baum, Herbert; Geißler, Torsten; Schneider, Jutta; Bühne, Jan-André: External Costs in the Transport Sector – A Critical Review of the EC Internalisation Policy. Study for the European Automobile Manufacturers Association (ACEA). May 2008

Behrends, Sylke: Neue politische Ökonomie. WiSo Kurzlehrbücher – Reihe Volkswirtschaft. München 2001

Bernhart, Wolfgang; Riederle, Stefan; Yoon, Manuel: Fuel cells. A realistic alternative for zero emission? Stuttgart 2014
Available at: http://www.rolandberger.com/media/pdf/Roland_Berger_Fuel_cells_20140113.pdf; Accessed: 02.02.2014

BGI, Berufsgenossenschaftliche Informationen für Sicherheit und Gesundheit bei der Arbeit. BG-Information 5108. BG Bahnen: Wasserstoffsicherheit in Werkstätten Stand Oktober 2009

Bitz, Michael; Delmmann, Klaus; Domsch, Michel; Egner, Henning (Publisher)*:* Vahlens Kompendium der Betriebswirtschaftslehre, Volume 1, Edition 3. Munich 1993

BMF, Bundesministerium der Finanzen: Monatsbericht des BMF – Februar 2008. Die Förderung von Biokraftstoffen seit 2004. Berlin, February 2008

BMF, Bundesministerium der Finanzen: Kassenmäßige Steuereinnahmen nach Steuerarten in den Kalenderjahren, Berlin 2015
Available at: https://www.bundesfinanzministerium.de/Content/DE/Standardartikel/Themen/-Steuern/Steuerschaetzungen_und_Steuereinnahmen/2015-06-16-steuereinnahmen-nach-steuerarten-2010-2014.pdf?__blob=publicationFile&v=11, Accessed: 16.07.2015

BMU, Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit: Börner, Alexandra; Hutfilter, Fuentes; Harnisch, Fuentes; Kracht, Astrid et.al. : Climate protection pays - Implementing and upgrading the Kyoto Protocol. Berlin September 2006
Available at: www.erneuerbare-energien.de/files/pdfs/allgemein/application/pdf/climate_protection_pays.pdf, Accessed 06.10.2007

BMVBS, Bundesministerium für Verkehr, Bau und Stadtentwicklung: Weichen stellen für morgen. Nachhaltigkeitsbericht des BMVBS. Berlin 25.02.2009
Available at: http://m.bundesregierung.de/Content/DE/_Anlagen/Nachhaltigkeit-wiederhergestellt/-bmvbs-nachhaltigkeitsbericht.pdf?__blob=publicationFile&v=2; Accessed. 17.02.2013

BMVBS, Bundesministerium für Verkehr, Bau und Stadtentwicklung, NOW: CEP. Join the movement. CEP Phase II, Berlin, April 2011
Available at: http://www.bmvbs.de/cae/servlet/contentblob/70234/publicationFile/41800/cep-brochure-hydrogen-let-it-move-you.pdf; Accessed: 28.05.2012

BMVBS, Bundesministerium für Verkehr, Bau und Stadtentwicklung: Die Mobilitäts- und Kraftstoffstrategie der Bundesregierung (MKS). Energie auf neuen Wegen. Berlin, Juni 2013
Available at: http://www.bmvbs.de/cae/servlet/contentblob/113880/publicationFile/79209/mks-strategie-final.pdf; Accessed: 07.07.2013

Bokow, Jacquelyn Cochran: Chicago Chooses Nonpolluting Fuel Cell Buses for City's Public Transit. Air Quality Grants, Stock Options Provide Financial Incentives. In: NHA News 1997

Book, Michael; Groll, Marcus; Mosquet, Xavier; Rizoulis, Dimitros; Sticher, Georg:BCG*:* The comeback of the electric car? How real, how soon and what must happen next? Düsseldorf 2009
Available at: https://www.bcg.com/documents/file15404.pdf; Accessed: 08.11.2015

Bosch (Editor): Kraftfahrtechnisches Taschenbuch. 26. Edition, Wiesbaden 2007

Bosch: Profitieren Sie von umfassender Start/Stopp-Kompetenz: Teile, Diagnose und Services von Bosch. No year
Available at: http://aa-boschap-de.resource.bosch.com/media/internet_public/parts/service_parts/-batteries/downloads_batteries/batteries_pkw.pdf; Accessed: 08.11.2015

***BP**:* BP Energy Outlook 2030. London, January 2012

BP: BP Statistical Review of World Energy, London, June 2014

Braess, Hans-Herrmann; Seiffert, Ulrich (Publ.): Vieweg Handbuch Kraftfahrzeugtechnik. Wiesbaden 2005

Brokate, Jens; Özdemir, Enver Doruk; Kugler, Ulrike; Friedrich, H.E. (DLR): Der Pkw-Markt bis 2040: Was das Auto von morgen antreibt. Szenario-Analyse im Auftrag des Mineralölwirtschaftsverbandes. Stuttgart 2013

Brown, Audley, Director Global Advanced Engine Engineering, GM: Looking from a hilltop: Automotive Propulsion System Technology. Michigan, 16.10.2012
Available at: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/deer_2012/tuesday/presentations/deer12_brown.pdf; Accessed: 20.02.2014

Bryson, John M.: What to do when stakeholders matter. Stakeholders identification and analysis techniques. In: Public Management Review, Vol. 6, Issue 1, 2004, p. 21 - 53

Bundesregierung: Perspektiven für Deutschland. Unsere Strategie für eine nachhaltige Entwicklung. Berlin 2002
Available at: http://www.bundesregierung.de/Content/DE/_Anlagen/Nachhaltigkeit-wiederhergestellt/perspektiven-fuer-deutschland-langfassung.pdf?__blob=publicationFile, Accessed: 08.11.2015

Bundesregierung: Fortschrittsbericht 2004. Perspektiven für Deutschland. Unsere Strategie für eine nachhaltige Entwicklung. Berlin 2004
Available at: http://www.nachhaltigkeitsrat.de/fileadmin/user_upload/dokumente/strategie_2004/-Fortschrittsbericht_2004.pdf, Accessed: 08.11.2015

***Bundesregierung**:* Fortschrittsbericht 2008 zur nationalen Nachhaltigkeitsstrategie. Für ein nachhaltiges Deutschland, Berlin Oktober 2008
Available at: http://www.bundesregierung.de/Content/DE/_Anlagen/Nachhaltigkeit-wiederhergestellt/2008-11-17-fortschrittsbericht-2008.pdf?__blob=publicationFile; Accessed: 08.11.2015

***CaFCP, California Fuel Cell Partnership**:* A California Road Map: The Commercialization of Hydrogen FCVs. The realization of fuel cell electric vehicles and supporting infrastructure requires a road map for investments in fuel cell electric vehicles and hydrogen fueling stations. California June 2012 (1)

CaFCP, California Fuel Cell Partnership: A California Road Map: Bringing Hydrogen Fuel Cell Electric Vehicles to the Golden State. California July 2012 (2)

CARB, California Air Resources Board: Attachment C. Final regulation order. Clean Fuels Outlets.
Availabe at: http://www.arb.ca.gov/fuels/altfuels/cf-outlets/attachc.pdf; Assessed: 10.01.2014

Carle, Gian; Wokaun, Alexander; Axhausen; K.W.: Market potential of CNG cars in the Swiss passenger car sector. In: World Transport Policy & Practice, Vol. 12, Number 2, Lancaster 2006
Available at: www.eco-logica.co.uk/pdf/WTPP12.2.pdf, Accessed: 01.01.2007

CEP Project data: Internal project document. 2011

Cerri, Sara: European hydrogen and FC activities overview and future technologies, New York, 2011
Available at: http://www.hydrogen.energy.gov/pdfs/htac_june2011_cerri.pdf, Accessed: 13.02.2013

ChemCoast et.al.: Kurzdarstellung: Fahrplan zur Realisierung einer Windwasserstoff-Wirtschaft in der Region Unterelbe. Hamburg 2013

Chen, Jixin; Siegel, Jason B.; Stefanopoulou, Anna G. (University of Michigan): Optimization of purge cycle for dead-ended anode fuel cell operation. In Proceedings of the ASME 2012 6th International Conference on Energy Sustainability & 10th FC Science, Engineering and Technology Conference. July 23-July 26, 2012, San Diego, USA
Available at: http://www-personal.umich.edu/~siegeljb/My_Papers/ASME12_Optimization_-study3.1.pdf; Accessed: 22.02.2014

CHIC: Demonstration of fuel cell buses in European field test. Presentation at the World Hydrogen Energy Conference. Toronto, Canada, 2012

Connor, Brendan: Low Carbon Transportation an epoch in the making. Presentation at the Low Carbon Vehicle Event, Cenex, UK, 2011

Cowan, Robin; Kline, David: The Implications of Potential “Lock-In” in Markets for Renewable Energy. NREL/TP-460-22112. November 1996, Golden, Colorado
Available at: http://www.nrel.gov/docs/legosti/fy97/22112.pdf; Accessed: 25.03.2013

Curtin, Sandra; Gangi, Jennifer; Skukowski, Ryan: The Business Case for Fuel Cells 2012. America’s Partner in Power. Washington D.C.
Available at: http://www.fuelcells.org/wp-content/uploads/2012/12/FC-Business-Case-2012.pdf; Accessed: 31.12.2012Washington D.C.

CUTE, Clean Urban Transport for Europe: Detailed summary of achievements. A hydrogen Fuel Cell Bus Project in Europe. 2001 – 2006. Vision, Teamwork and Technology. Ulm, Germany 2005

Deutscher Bundestag: Gesetz für den Vorrang Erneuerbarer Energien (Erneuerbare-Energien-Gesetz – EEG). 30.06.2011. in der ab 1. Januar 2012 geltende Fassung

Deutscher Bundestag: Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (KSpG). Ausfertigungsdatum: 17.08.2012

Diez, Willi; Kohler, Markus*:* IHK Region Stuttgart: Otto-, Diesel-, Elektromotor – wer macht das Rennen? Handlungsfelder zur Sicherung des Automobilstandorts Region Stuttgart. Stuttgart 2010
Available at: http://www.automotive-rheinland.de/content/Green_Mobility_280910.pdf, Accessed: 08.11.2015

Dinger, Andreas; Martin, Ripley; Masquet, Xavier et. al.*:* BCG Focus: Batteries for Electric Cars. Challenges, Opportunities, and the Outlook to 2020. Munich 2010
Available at: www.bcg.de/documents/file36615.pdf; Accessed: 12.12.2011

Dinse, Gundi: Akzeptanz von wasserstoffbetriebenen Fahrzeugen. Eine Studie über die Verwendung eines neuen und ungewohnten Kraftstoffs. Institut für Mobilitätsforschung, Berlin 2001
Available at: http://www.ifmo.de/tl_files/publications_content/2000/ifmo_2000_Akzeptanz_-von_wasserstoffbetr_Fahrzeugen_de.pdf; Accessed: 30.01.2013

DOE, Department of Energy, Energy Efficiency and Renewable Energy*:* Hydrogen & Our Energy Future. No year (1)
Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogenenergyfuture_web.-pdf; Accessed: 25.11.2012

DOE, Department of Energy, Energy Efficiency and Renewable Energy: Fuel cell technologies program. Hydrogen production.Fuel Cells. No year (2)
Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_production.pdf; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fct_h2_fuelcell_factsheet.pdf; Accessed: 25.11.2012

DOE, Department of Energy, Energy Efficiency and Renewable Energy*:* Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles. No year (3)
Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_-hydro_storage.pdf; Accessed: 12.04.2012

DOE, Department of Energy, Energy Efficiency and Renewable Energy, Freedom Car Fuel Partnership: Targets for Onboard Hydrogen Storage Systems for LDVs. September 2009 (1)
Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_-hydro_storage_explanation.pdf; Accessed: 23.10.2010

DOE, Department of Energy, Energy Efficiency and Renewable Energy: Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs. October 2009 (2)
Available at: http://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_-gas_compression.pdf; Accessed: 23.04.2013

DOE, Department of Energy, Energy Efficiency and Renewable Energy*:* DOE Hydrogen Program Record. Washington DC, September 2010
Available at: http://www.hydrogen.energy.gov/pdfs/10004_fuel_cell_cost.pdf; Accessed: 02.02.2013

DOE, Department of Energy, Energy Efficiency and Renewable Energy*:* 2010 Fuel Cell Technologies Market Report. Washington DC, June 2011
Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2010_market_report.pdf; Accessed: 01.12.2012

DOE, Department of Energy, Energy Efficiency and Renewable Energy*:* Technical Plan-Fuel Cells. 2012
Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf; Accessed: 22.02.2014

DOE, Department of Energy, Energy Efficiency and Renewable Energy*:* Biochemical Conversion: Using Enzymes, Microbes, and Catalysts to Make Fuels and Chemicals. July 2013
Available at: http://www1.eere.energy.gov/bioenergy/pdfs/biochemical_four_pager.pdf; Accessed: 03.03.2014

Downs, Anthony*:* An Economic Theory of Democracy. New York 1957

EC: Legal documents of the European Commission are available from the Eurolex Database using the respective year of publication, the document number and the document type: http://eur-lex.europa.eu/en/index.htm

EC, European Commission*:* Council Directive of 13.09.1993 to limit carbon dioxide emissions by improving energy efficiency (SAVE) (**93/76/EEC**). Brussels 22.09.1993, Accessed 14.09.2007

EC, European Commission*:* Commission Directive **93/116/EC** of 17. December 1993 adapting to technical progress Council Directive 80/1268/EEC relating to the fuel consumption of motor vehicles. Accessed 12.04.2007

EC, European Commission*:* Council **Directive 96/62/EC** of 27 September 1996 on Ambient Air Quality Assessment and Management. Brussels 20.11.2003, Accessed 20.02.2008

EC, European Commission*:* **Directive 98/70/EC** of the European Parliament and of the Council relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC. Brussels, 13 October 1998, Accessed 12.04.2007

EC, European Commission*:* Communication from the Commission: A Review of the Auto-Oil II Programme. **COM(2000)626 final.** Brussels, 05.10.2000, Accessed 12.04.2007

EC, European Commission*:* Green Paper - Towards a European strategy for the security of energy supply. **COM(2000)769 final**. Brussels, 29 November 2000, Accessed 29.09.2007

EC, European Commission*:* White Paper: European transport policy for 2010: time to decide. **COM(2001)370**. Brussels, 12 September 2001, Accessed 29.09.2007

EC, European Commission: **Directive 2001/81/EC** of the EP and of the Council on national emission ceilings for certain atmospheric pollutants, Brussels 27.11.2001, Accessed 29.09.2007

EC, European Commission*:* **Directive 2003/17/EC** of the EP and of the Council of 3 March 2003 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels. Brussels 22.3.2003, Accessed 12.04.2007

EC, European Commission: Work programme. 6.1 Sustainable energy systems. Revision 2. Brussels, April 2004

EC, European Commission*:* Green Paper on Energy Efficiency or Doing More With Less. **COM(2005)265final**. Brussels, 22.06.2005, Accessed 29.09.2007

EC, European Commission: Proposal for a Council Directive on passenger car related taxes **COM(2005)261**. Brussels, 05.07.2005, Accessed: 13.03.2008

EC, European Commission, CAFE Programme: Commission staff Working Paper: Impact Assessment of the Thematic Strategy on Air Pollution and the Directive on “Ambient Air Quality and Cleaner Air for Europe” – **Summary / Country Data**. Brussels, September 2005. Brussels, September 2005

EC, European Commission*:* Green Paper – A European Strategy for Sustainable, Competitive and Secure Energy. **COM(2006)105 final**. SEC(2006) 317. Brussels, 08.03.2006, Accessed 29.09.2007

EC, European Commission*:* Communication from the Commission to the council, the European parliament, the European Economic and Social Committee and the Committee of the Regions. Building a global carbon market – Report pursuant to Article 30 of Directive 2003/87/EC. **COM(2006)676 final**. Brussels, 13.11.2006, Accessed 29.09.2007

EC, European Commission: Communication from the Commission to the Council and the European Parliament. Results of the review of the Community Strategy to reduce CO_2 emissions from passenger cars and light-commercial vehicles. **COM(2007)19 final**. Brussels 7.2.2007, Accessed 17.12.2007

EC, European Commission: Regulation (EC) **No 715/2007** of the European Parliament and of the Council on type approval of motor vehicles with respect to emissions from light passenger and commercialvehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information. Brussels, 20 June 2007 Accessed 31.12.2007

EC, European Commission: Proposal for a regulation of the European Parliament and of the Council. Setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles. **COM(2007)856**. Brussels, 19.12.2007, Accessed 31.12.2007

EC, European Commission: Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. **COM(2008)19,** Brussels 23.01.2008, Accessed: 05.03.2010

EC, European Commission: **Directive 2008/50/EC** of the European Parliament and of the Council on ambient air quality and cleaner air for Europe. Brussels, 21 May 2008, Accessed: 05.03.2010

EC, European Commission: Commission Regulation (EC) **No 692/2008** implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information. Brussels, 18 July 2008, Accessed: 12.05.2012

EC, European Commission: **Regulation (EC) No 79/2009** of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC. Brussels, 14 January 2009, Accessed: 24.06.2012

EC, European Commission: **Regulation (EC) No 443/2009** of the European Parliament and of the Council setting emission performance standards for new passenger cars as part of the Community's integrated approach to reduce CO_2 emissions from light-duty vehicles, Brussels, 23 April 2009, Accessed: 24.06.2010

EC, European Commission: **Directive 2009/28/EC** of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Brussels, 23 April 2009, , Accessed: 24.06.2010

EC, European Commission: **Directive 2009/30/EC** of the European Parliament and of the Council amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions. Brussels, 23 April 2009, Accessed: 24.06.2010

EC, European Commission: Communication from the Commission to the Council and the European Parliament. The European Strategic Energy Technology Plan. **SET-Plan**. Towards a low-carbon future. Information Brochure. Brussels, 2010

EC, European Commission: Europe 2020 - A strategy for smart, sustainable and inclusive growth. **COM(2010)2020** final. Brussels, 3.3.2010, Accessed: 15.04.2012

EC, European Commission: Communication from the Commission to the Council and the European Parliament. Car prices within the European Union. Competition Reports. Brussels 2011
Available at: http://ec.europa.eu/competition/sectors/motor_vehicles/prices/2011_07_full.pdf; Accessed: 24.02.2014

EC, European Commission: Communication from the Commission to the Council and the European Parliament. A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy. **COM(2011)21 final**. Brussels, 26.1.2011, Accessed: 15.04.2012

EC, European Commission: White Paper. Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. **COM(2011)144** final Brussels, 28.3.2011, Accessed: 15.04.2012

***EC, European Commission**:* Proposal for a Council Directive amending Directive 2003/96/EC restructuring the Community framework for the taxation of energy products and electricity. **COM(2011)169 final**. Brussels, 13.4.2011, Accessed: 22.12.2011

EC, European Commission: Communication from the Commission to the Council and the European Parliament. A Roadmap for moving to a competitive low carbon economy in 2050. **COM(2011)112 final/2**. Brussels, 25.5.2011, Accessed: 15.05.2012

***EC, European Commission**:* Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EC) No 443/2009 to define the modalities for reaching the 2020 target to reduce CO2 emissions from new passenger cars. **COM(2012)393 final**, Brussels, 11.7.2012, Accessed: 22.12.2011

***EC, European Commission**:* **Draft Horizon 2020** Work Programme 2014-2015 in the area of Transport. Brussels, 2013
Available at: http://ec.europa.eu/research/horizon2020/pdf/work-programmes/smart_green_and_-integrated_transport_draft_work_programme.pdf; Assessed: 01.01.2014

***EC, European Commission**:* Proposal for a Directive of the European Parliament and of the Council on the deployment of alternative fuels infrastructure. **COM(2013)18 final**. Brussels, 24.1.2013, Accessed: 26.12.2013

***EC, European Commission**:* A policy framework for climate and energy in the period from 2020 to 2030. **COM(2014)15 final**. Brussels, 22.01.2014, Accessed: 25.03.2014

EC, DG Competition, European Commission: Paper of the Services of DG Competition containing draft Guidelines on environmental and energy aid for 2014-2020. Brussels 2013
Available at: http://ec.europa.eu/competition/consultations/2013_state_aid_environment/index_de.-html; Assessed: 25.03.2014

EC, DG Energy in collaboration with DG Climate Action and DG Mobility and Transport, European Commission: European energy trends to 2030 - Update 2009. Brussels 2010
Available at: https://ec.europa.eu/energy/sites/ener/files/documents/trends_to_2030_update_-2009.pdf; Accessed: 08.09.2012

***EC, DG Energy in collaboration with DG Climate Action. DG Mobility and Transport, European Commission**:* EU energy, transport and GHG emissions trends to 2050. Reference Scenario 2013. Brussels December 2013
Available at*:* http://ec.europa.eu/transport/media/publications/doc/trends-to-2050-update-2013.pdf; Accessed: 25.02.2014

***EC, DG Enterprise and Industry, European Commission**:* CARS21 - A Competitive Automotive Regulatory System for the 21st century. Final Report. Brussels 2006

***EC, DG Research, European Commission**. Sustainable Energy Systems:* European Fuel Cell and Hydrogen Projects 2002-2006. EUR 22398. Brussels 2006
Available at: ftp://ftp.cordis.europa.eu/pub/fp7/energy/docs/hydrogen_synopses_en.pdf; Accessed: 29.04.2012

***EC, DG Research, European Commission.** Joint Research Centre, Institute for Prospective Technological Studies: Guevara, Héctor Hernández; Tübke, Alexander; Brandsma, Andries*: The 2008 EU Industrial R&D Investment Scoreboard. EUR 23530 EN. Luxembourg. 2008
Available at: http://iri.jrc.ec.europa.eu/research/docs/2008/Scoreboard_2008.pdf, Accessed: 04.01.2009

***EC, DG Research, European Commission.** Joint Research Centre*: The 2012 EU Industrial R&D Investment Scoreboard. Luxembourg, 2013 (1)
Available at: http://iri.jrc.ec.europa.eu/documents/10180/11522/The%202012%20-EU%20Industrial%20R%26D%20Investment%20Scoreboard, Accessed: 15.08.2013

***EC, DG Research, European Commission.** Joint Research Centre*: The 2013 EU Industrial R&D Investment Scoreboard. Luxembourg, 2013 (2)
Available at: http://iri.jrc.ec.europa.eu/scoreboard13.html, Accessed: 23.01.2014

***EC, DG Taxation and Customs Union, Tax Policy, European Commission**,:* Excise duties and transport, environment and energy taxes. REF 1.026: Excise duty tables. Part II – Energy products and Electricity. In accordance with the Energy Directive (2003/96/EC) including Natural Gas, Coal and Electricity. January 2008
Available at: http://ec.europa.eu/taxation_customs/resources/documents/taxation/excise_duties/-energy_products/rates/excise_duties-part_II_energy_products-en.pdf, Accessed: 27.03.2008

***Edwards, R.; (European Commission Joint Research Centre, Institute for Energy); Larivé, J-F. (CONCAWE); Beziat, J-C. (Renault/EUCAR)**:* Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context. Well-to-Wheels Report. JRC Scientific and Technical Reports. EUR 24952 EN – 2011. Version 3c, Brussels July 2011 (1)
Available at: http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw3_wtw_report_eurformat.pdf; Accessed: 25.12.2011

Appendix 1: Summary of WtW Energy and GHG balances, Brussels July 2011 (2)
Available at: http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw3_wtw_appendix1_eurformat.pdf; Accessed: 25.12.2011

Appendix 2: WtW GHG-Emissions of Externally Chargeable Electric Vehicles, Brussels July 2011 (3)
Available at: http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw3_wtw_appendix2_eurformat.pdf; Accessed: 25.12.2011

***EEA, European Environment Agency**:* Ten key transport and environment issues for policymakers. TERM 2004: Indicators tracking transport and environment integration in the European Union. Report No. 03/2004. Copenhagen 2004
Available at: http://www.eea.europa.eu/publications/TERM2004, Accessed 29.05.2007

EEA, European Environment Agency: Monitoring CO_2-emissions from new passenger cars in the EU: Summary of data for 2011. Copenhagen, 2012
Available at: http://www.eea.europa.eu/publications/monitoring-co2-emissions-from-new/at_download/file; Accessed: 27.10.2012

EEA, European Environment Agency: CO_2-emissions performance of car manufacturers in 2012. Copenhagen 2013
http://www.eea.europa.eu/publications/co2-emissions-performance-of-car-1; Accessed: 24.02.2014

Ehret, Oliver: Nationale Initiativen für Wasserstoff als marktnahe Querschnittstechnologie. DBI-Fachforum Energiespeicher–Hybridnetze Berlin, 12. September 2012
Available at: http://www.eti-brandenburg.de/fileadmin/user_upload/downloads2011/Energietag_-2011/03_Dr._Oliver_Ehret__NOW_GmbH.pdf; Accessed: 08.11.2015

EIA, Energy Information Administration: Office of Energy Markets and End Use: Performance Profiles of Major Energy Producers 2006. DOE/EIA-0206(06). Washington, DC, December 2007

***Encyclopaedia Britannica**:* The new Encyclopaedia Britannica. Fifteenth edition. Chicago, Auckland, London et. al. 1994

Enertrag: Fragen und Antworten Enertrag Hybridkraftwerk, 2012
Available at: https://www.enertrag.com/download/praesent/FAQ_Hybridkraftwerk_11122012.pdf; Accessed: 08.11.2015

Engel, Thomas: Solare Mobilität: Plug-in Hybrids. Studie zur Abschätzung des Potentials zur Reduktion der CO_2-Emissionen im PKW-Verkehr bei verstärkter Nutzung von elektrischen Antrieben im Zusammenhang mit Plug-in Hybrid Fahrzeugen. München September 1997

European Council: Council Regulation (EC) **No. 521/2008** of 30 May 2008 setting up the Fuel Cells and Hydrogen Joint Undertaking, Brussels, 12.06.2008
Available at: http://ec.europa.eu/research/fch/pdf/regulation_521-2008__en_1.pdf#view=fit&pagemode=none, Accessed: 17.02.2011

***Eurostat**:* EU transport in figures. Statistical pocketbook 2012. Luxembourg, 2012
Available at: http://ec.europa.eu/transport/facts-fundings/statistics/doc/2012/pocketbook2012.pdf, Accessed: 12.02.2013

Eurostat: *Statistics*: Table: Gross inland consumption of primary energy, 1,000 toe, http://ec.europa.eu/eurostat/; Accessed: 16.09.2015

Exzellenz NRW: Netzwerk Brennstoffzelle und Wasserstoff. Gebündelte Kompetenz für Energieeffizienz und Klimaschutz in Nordrheinwestfalen. No year
Available at: https://broschueren.nordrheinwestfalendirekt.de/herunterladen/der/datei/nbw-broschuere-final-pdf/von/netzwerk-brennstoffzelle-und-wasserstoff-gebuendelte-kompetenz-fuer-energieeffizienz-und-klimaschutz-in-nrw/vom/energieagentur/1161; Accessed: 12.02.2014

EY (Ernest Young): US upstream: costs, prices and the unconventional treadmill. 2014
Available at: http://www.ey.com/Publication/vwLUAssets/EY-US-upstream-costs-prices-and-the-unconventional-treadmill/$FILE/EY-US-upstream-costs-prices-and-the-unconventional-treadmill.pdf; Accessed: 05.07.2015

Freeman, R. Edward: Strategic management. A shareholder approach. Boston 1984

Friedrich, Jürgen K.H.: Hydrogen for smart mobility. Dutch Hydrogen and Fuel Cell Association, Arnhem, The Netherlands, 04.10.2012

FuelCell Today: Industry Review 2011. Herts, UK, July 2011
Available at: http://www.fuelcelltoday.com/analysis/industry-review/2011/the-industry-review-2011; Accessed: 02.12.2012

FuelCell Today: Fuel Cells and Hydrogen in Norway. Herts, UK, December 2012
Available at: http://www.fuelcelltoday.com/media/1838763/fuel_cells_and_hydrogen_in_nor-way.pdf; Accessed: 23.05.2013

FuelCell Today: Latest Developments in the Ene-FarmScheme. Herts, UK, February 2013
Available at: http://www.fuelcelltoday.com/media/1846139/13-02-27_latest_developments_in_the_-ene-farm_scheme.pdf; Accessed: 12.02.2014

FuelCell Today: Fuel Cell Electric Vehicles: The Road Ahead. Herts, UK, July 2013 (2)
Available at: http://www.fuelcelltoday.com/media/1711108/fuel_cell_electric_vehicles_-_the_road_-ahead_v3.pdf; Accessed: 12.02.2014

Fulton, Lewis M. (Global Fuel Efficiency Initiative): How vehicle fuel economy improvements can save $2 trillion and help fund a long-term transition to plug-in vehicles. Working Paper 9. London 2013
Available at: http://www.globalfueleconomy.org/media/44075/wp9-fuel-economy-improvements.pdf; Accessed: 08.11.2015

Fumatech: Product Information: Membrane Humidifiers, fumasep, Ecomate High Performance Membrane Humidifiers for Fuel Cells. Bietigheim-Bissingen. No year

GermanHy: Im Auftrag des Bundesministeriums für Verkehr, Bau und Stadtentwicklung (BMVBS) und in Abstimmung mit der Nationalen Organisation Wasserstoff- und Brennstoffzellentechnologie (NOW). Joest, Steffen (dena); Fichtner, Maximilian (Forschungszentrum Karlsruhe GmbH); Bünger, Ulrich, Stiller, Christoph; Schmidt, Patrick (Ludwig-Bölkow-Systemtechnik). Studie zur Frage „Woher kommt der Wasserstoff in Deutschland bis 2050?“ Berlin August 2009. June, 2008
Available at: http://www.dena.de/fileadmin/user_upload/Publikationen/Verkehr/Dokumente/german-Hy_Abschlussbericht.pdf; 08.11.2015

Gillingham, Kenneth: Hydrogen Internal Combustion Engine Vehicles: A Prudent Intermediate Step or a Step in the Wrong Direction? Stanford, January 2007
Available at: http://www.yale.edu/gillingham/hydrogenICE.pdf; Accessed: 10.11.2012

Greene, David L.; Ahmad, Sanjana:Oak Ridge National Laboratory for the US Department of Energy, Report N°: ORNL/TM-2005/45: Costs of U.S. Oil Dependence: 2005 Update. Oak Ridge, Tennessee, January 2005
Available at: http: http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM2005_45.pdf, Accessed 12.10.2006

Greene, David L. (Oak Ridge National Laboratory): Status and Prospects of the Global Automotive Fuel Cell Industry and Plans for Deployment of Fuel Cell Vehicles and Hydrogen Refueling Infrastructure. ORNL/TM-2013/222. Juli 2013
Available at: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fcev_status_prospects_july-2013.pdf; Accessed: 05.02.2014

Grube, Thomas; Höhlein, Bernd: Kosten des Wasserstoffbereitstellung in Versorgungssystemen auf Basis erneuerbarer Energien. In: Töpler, Johannes; Lehmann, Jochen: Wasserstoff und Brennstoffzelle; Technologien und Marktperspektiven. Berlin 2013

Grube, Thomas; Schiebahn, Sebastian; Stolten, Detlef; Tietze, Vanessa (Forschungszentrum Jülich): Die Rolle elektrochemischer Wandler und Speicher in der Energiewende. FGE-Kolloquium. Wintersemester 2013/2014. Aachen, 23.01.2014
Available at: http://www.fge.rwth-aachen.de/fileadmin/Uploads/PDF/FGE_Kolloquium_2013-2014/FGE_Kolloquiumsvortrag_Herr_Grube.pdf; Assessed: 01.03.2014

gvr, Gas Vehicles Report: various issues, Editor: NGV communications group. Available at: http://www.ngvjournal.com/en/magazines/the-gvr

Hacker, Florian; Harthan, Ralph; Kasten, Peter; Loreck, Charlotte; Zimmer, Wiebke (Ökoinstitut e.V.): Marktpotenziale und CO_2-Bilanz vonElektromobilität. Arbeitspakete 2 bis 5 des Forschungs-vorhabensOPTUM: Optimierung derUmweltentlastungspotenziale von Elektrofahrzeugen. Anhang zum Schlussbericht im Rahmen der Förderung vonForschung und Entwicklung im Bereich der Elektromobilitätdes Bundesministeriums für Umwelt, Naturschutz undReaktorsicherheit. Berlin, October 2011
Available at: http://www.oeko.de/oekodoc/1338/2011-002-de.pdf, Assessed: 31.01.2012

Häder, Michael*:* Delphi-Befragungen. Ein Arbeitsbuch. Wiesbaden, March 2002

Harris, Garth*:* Who will harmonize the harmonizers? In: NGV Worldwide: An International Publication for the Natural Gas Vehicles Industry. Auckland, New Zealand, May 2004

Hart, David: Der Hart-Report: Die Ökonomie einer europäischen Infrastruktur für wasserstoffbetriebene Fahrzeuge. 2005
Available at: http://www.hydrogenday.de/International/Web/Hydrogenday2005.nsf/mediaback-grounder_dt.pdf, Accessed: 29.12.2012

Hartman, Francis T.; Krahn, Jennifer; Skulmoski, Gregory J.*:* The Delphi Method for Graduate Research. In: Journal of Information Technology Education Vol. 6, Dubai, Calgary 2007
Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.151.8144&rep=rep1&type=-pdf, Accessed: 08.11.2015

Haupt, Reinhard; Jahn, Karsten; Lange, Marcus; Ziegler, Wolfgang*:* Der Patentlebenszyklus: Methodische Lösungsansätze der externen Technologieanalyse. In: Jenaer Schriften zur Wirtschaftswissenschaft 24/2004. Arbeits- und Diskussionspapiere der Wirtschaftswissen-schaftlichen Fakultät der Friedrich-Schiller-Universität. Jena, Germany 2004
Available at: http://www.wiwi.uni-jena.de/Papers/wp-sw2404.pdf, Accessed: 18.04.2008

Hedinger: Sicherheitsdatenblatt gemäß Verordnung (EU) Nr. 453/2010 Benzin 100 / 140 überarbeitet am: 11.08.2011
Available at: http://www.hedinger.de/uploads/media/Benzin_100-140_v015_01.pdf; Accessed: 08.11.2015

Herbert, Thorsten*:* Wasserstoffantriebe in der Praxis. Vision oder Standard der Zukunft – Alternative Fahrzeugantriebe im Vergleich. Hamburg, 30. October 2013
Available at: http://www.hk24.de/linkableblob/hhihk24/innovation/downloads/2642458/.4./-data/Vortrag_Wasserstoffantriebe_in_der_Praxis-data.pdf; Accessed: 23.12.2013

Heslin Rothenberg Farley; Mesiti P.C.: Clean Energy Patent Growth Index. Results 2013, 2014 (1)
Available at: http://cepgi.typepad.com/files/cepgi-2013-year-end-wrap-up.pdf; Accessed: 08.08.2014

Heslin Rothenberg Farley; Mesiti P.C.: Clean Energy Patent Growth Index. First Quarter Results 2014, 2014 (2)
Available at: http://cepgi.typepad.com/files/cepgi-1st-quarter-2014.pdf; Accessed: 08.08.2014

Heymann, Eric; Koppel, Oliver; Puls, Thomas*:* (Deutsche Bank Research; Institut der deutschen Wirtschaft Köln)*:* Elektromobilität. Sinkende Kosten sind conditio sine qua non. Aktuelle Themen 526. Frankfurt, September 2011
Available at: https://www.db.com/cr/de/docs/DB_Research_-_Elektromobilitaet_Sept._2011_%28-de%29.pdf; Accessed: 08.11.2015

High Level Group for Hydrogen and Fuel Cells: Hydrogen energy and fuel cells. A vision for our future. High Level Group for Hydrogen and Fuel Cells. Summary Report. Brussels, June 2003
Available at: http://www.epsoweb.eu/catalog/tp/Vision_EUHydrogenEnergy&FuelCells_Jun-20031.pdf, Accessed: 10.02.2011

Hollemann, A. F.; Wiberg, Egon; Wiberg, Nils: Berlin, New York 1985

HSL, Health and Safety Laboratory: Spontaneous ignition of hydrogen. Literature Review.
Available at: http://www.hse.gov.uk/research/rrpdf/rr615.pdf, Accessed: 12.04.2012

Hsu, Chia-Chien;. Sandford, Brian A.: The Delphi Technique: Making Sense Of Consensus. In: Practical Assessment, Research & Evaluation. Volume 12, Number 10, August 2007
Available at: http://pareonline.net/getvn.asp?v=12&n=10, Accessed: 27.02.2010

Huizing, Ryan (University of Waterloo): Design and Membrane Selection for Gas to Gas Humidifiers for Fuel Cell Applications. 2007. In: https://uwspace.uwaterloo.ca/handle/10012/3048

HydrogenHighway: Project brochure. BC Hydrogen Highway Business Plan. Executive Summary. Canada. No year

HyNet: Towards a European Hydrogen Energy Roadmap Preface to HyWays – the European Hydrogen Energy Roadmap Integrated Project. Executive Summary – Abstract, 12 May 2004
Available at: http://www.hyways.de/hynet/HYNET-roadmap_ABSTRACT_MAY2004.pdf, Accessed: 25.01.2008

HyWays: Roadmap and Action Plan. Executive Summary of the European Hydrogen Energy. Roadmap and Action Plan. Ottobrunn, February 2008
Available at: http://www.hyways.de/docs/Brochures_and_Flyers/HyWays_executive_summary_-FINAL_22FEB2008.pdf; Accessed: 08.11.2015

Icha, Petra (Umweltbundesamt). Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2013. Climate Change 23/2014
Available at: http://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/-climate_change_23_2014_komplett.pdf; Accessed: 24.08.2014

ifmo*:* The Future of MobilityScenarios for the Year 2025. First Update. 2002

Institut für Wachstumsstudien: Kernaussage des Instituts für Wachstumsstudien. 2. Issue (2008)
Available at: http://www.wachstumsstudien.de/Inhalt/PDF/IWS_Kernaussage.pdf; Accessed: 25.02.2013

IEA, International Energy Agency: Energy technology perspectives. In support of the G8 plan of action. Strategies and Scenarios to 2050. Paris 2008
Available at: http://www.iea.org/publications/freepublications/publication/etp2008.pdf; Accessed: 01.02.2013

IEA, International Energy Agency: *T'Serclaes, Philippine de; Gasc, Emilien; Saussay, Aurélien*: Energy Efficiency Series: Information Paper: Financial Crisis and Energy Efficiency. Paris, France, 2009 (1)

IEA, International Energy Agency*:* World Energy Outlook 2009. Fact Sheet. Why is our current energy pathway unsustainable? Paris, France 2009 (2)

IEA, International Energy Agency: CO_2 emissions from fuel combustion. IEA statistics highlights 2012. Paris 2012

IEA, International Energy Agency*:* Global EV Outlook: Understanding the Electric Vehicle Landscape to 2020. 2013 (1)
Available at: http://www.iea.org/publications/globalevoutlook_2013.pdf; Accessed: 07.02.2014

IEA, International Energy Agency*: Baroni, Marco:* The World Energy Model. 2013 (2)
Available at: http://www.iea.org/media/weowebsite/2013/iew2013/IEW2013WEOpresentations.pdf; Accessed: 07.02.2014

IEA, International Energy Agency*:* Resources to Reserves 2013. Oil, gas and coal technologies for the energy markets of the future. 2014
Available at: http://www.iea.org/Textbase/npsum/resources2013SUM.pdf; Accessed: 28.08.2014

***IEA/HIA, International Energy Agency/*HIA**: Task 25: High temperature hydrogen production process. No year
Available at: http://ieahia.org/pdfs/alkaline-electrolysis.aspx; Accessed. 12.02.2014

IEA/OECD, International Energy Agency/OECD*:* Experience Curves for Energy Technology Policy. Paris, France 2000
Available at: http://www.wenergy.se/pdf/curve2000.pdf, Accessed 22.11.2006

IEA/OECD, International Energy Agency/OECD: Creating Markets for Energy Technologies. Paris, France 2003

IEA/OECD, International Energy Agency/OECD: How the energy sector can deliver on a climate agreement in Copenhagen. Special early exerpt of the World Energy Outlook 2009 for the Bangkok UNFCCC meeting. Paris, October 2009
Available at: http://www.iea.org/publications/freepublications/publication/climate_change_-excerpt.pdf; Accessed: 30.03.2010

IPCC, Intergovernmental Panel on Climate Change. *Solomon, S.; Qin, D.; Manning, M.; Chen, Z. ; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller; H.L. (eds.):* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. **Frequently Asked Questions**. Cambridge, United Kingdom and New York, NY, USA, 2007 (1)
Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-faqs.pdf, Accessed: 22.01.2007

IPCC, Intergovernmental Panel on Climate Change. *Solomon, S.; Qin, D.; Manning, M.; Chen, Z. ; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller; H.L. (eds.):* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. **Summary for Policy Makers**. Cambridge, United Kingdom and New York, NY, USA, 2007 (2)
Available at: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf, Accessed: 22.01.2007

IPCC, Intergovernmental Panel on Climate Change. *Field, C.B., V. Barros, T.F. Stocker, D. Qin, et. al.:* Summary for Policymakers. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, USA, 2012
Available at: http://ipcc-wg2.gov/SREX/images/uploads/SREX-SPMbrochure_FINAL.pdf, Assessed: 21.02.2014

IPCC, Intergovernmental Panel on Climate Change. *Stocker, Thomas F.; Qin, Dahe; Plattner, Gian-Kasper; Tignor, Melinda M.B.; Allen, Simon K.; Boschung, Judith et.al.*: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for Policymakers. Switzerland 2013
Available at: http://www.climatechange2013.org/images/report/WG1AR5_SPM_FINAL.pdf; Assessed: 21.02.2014

IPHE: IPHE Infrastructure Workshop. Workshop Proceedings. Sacramento 2010
Available at: http://www.iphe.net/docs/Events/iphe_infrastructure_workshop_feb2010.pdf; Accessed: 02.06.2010

Itron, Inc.: CPUC Self-Generation. Incentive Program.Cost-Effectiveness of Distributed Generation Technologies. Final Report. California, February 2011
Available at: http://www.cpuc.ca.gov/NR/rdonlyres/2EB97E1C-348C-4CC4-A3A5-D417B4DDD-58F/0/SGIP_CE_Report_Final.pdf

Jianyi, Lin: Catalysts for PEM Fuel Cells. Singapore Catalysis Society 2011. Workshop. Singapore 2011
Available at: http://www.catalysis.org.sg/images/resource/fuel%20cell.pdf; Accessed: 01.12.2012

Jörissen, Ludwig; Garche, Jürgen: Polymerelektrolytmembran-Brennstoffzellen (PEFC) Stand und Perspektiven. In: Töpler, Johannes; Lehmann, Jochen: Wasserstoff und Brennstoffzelle; Technologien und Marktperspektiven. Berlin 2013

Joseph, Tom: NFPA 52 and 55 brief review. WHTC 2009 & US DOE C&S Workshop August 29, 2009 Available at: http://www.hpath.org/proceedings/BHI-Joseph-DOE%20India%20CS2009.pdf; Accessed 04.11.2012

Karlsruher Institut für Technologie: Erstmals Benzin am KIT hergestellt. Presseinformation Nr. 119, 27.09.2013
Available at: http://www.bioliq.de/downloads/KIT_PI_2013_119_Erstmals_Benzin_am_KIT_hergestellt.pdf; Accessed: 03.03.2014

kba, Kraftfahrt-Bundesamt: Schadstoff-Typprüfwerte von Kraftfahrzeugen zur Personenbeförderung mit höchstens neun Sitzplätzen und Wohnmobilen. 2012

kba publishes several annual statistical reports available at http://www.kba.de/DE/Statistik/-statistik_node.html, incuding

fz8 report: Fahrzeugzulassungen. Neuzulassungen von Kraftfahrzeugen und Kraftfahrzeuganhängern – Monatsergebnisse

fz11 report: monthly report, Neuzulassungen von Personenkraftwagen nach Segmenten und Modellreihen

fz13 report: Fahrzeugzulassungen, Bestand an Kraftfahrzeugen nach Umwelt-Merkmalen

fz14 report: Neuzulassungen von Kraftfahrzeugen nach Umwelt-Merkmalen

Table 1: Neuzulassungen von Personenkraftwagen im Jahr 2014 nach Segmenten und ausgewählten technischen Merkmalen
Available at: http://www.kba.de/DE/Statistik/Fahrzeuge/Neuzulassungen/Motorisierung/motorisierung_node.html

Kelly, Ruth; Mikhail, Monique; Herman, Marc-Olivier: Oxfam briefing paper 161: The hunger grains the fight is on. Time to scrap EU biofuel mandates. 17 September 2012
Available at: http://www.oxfam.org/sites/www.oxfam.org/files/bp161-the-hunger-grains-170912-en.pdf; Accessed: 31.10.2012

Kirchgässner, Gebhard; Schneider, Friedrich: Zur politischen Ökonomie der Umweltpolitik: Hat die Politikberatung etwas bewirkt? Einige Überlegungen aus der Perspektive der Neuen Politischen Ökonomie. In: Zeitschrift für angewandte Umweltforschung. Sonderheft 15 (2002), S. 1-29

Kirsch, Guy: Neue Politische Ökonomie. 5. Auflage Stuttgart 2004

Klell, Manfred; Kindermann, Harald; Jogl, Christian: Thermodynamics of gaseous and liquid hydrogen storage. Graz 2007
Available at: http://www.hycenta.tugraz.at/Image/Thermodynamics%20of%20gaseous%20and-%20liquid%20hydrogen%20storage.pdf; Accessed: 29.12.2012

Klell, Manfred: Storage of Hydrogen in the Pure Form. In: Handbook of Hydrogen Storage. 2010
Available at: http://www.wiley-vch.de/books/sample/3527322736_c01.pdf; Accessed: 12.04.2014

Kotler, Philip: Marketing Management – Analysis, Planning, Implementation and Control. 9th edition, New Jersey 1997

Krainz, Günter; Hödl, Peter; Hofmeister, Franz: Automotive Production of Liquid Hydrogen Storage Systems, Graz 2004
Available at: http://www.storhy.net/pdf/IntH2_KRAINZ_2004-02-11.pdf; Accessed: 04.09.2011

Kroher, Thomas: Wird der Diesel bald teurer? In: ADAC-Motorwelt 8/2009. p. 22-25

Krüger, R.: Session 1.4: Introductory Lectures. Design Aspects of Pressurized Hydrogen Storage Systems. StorHy. 2006
Available at: http://www.storhy.net/train-in/PDF-TI/06_STORHY_Train-IN_Session_1_4_RKrueger.pdf; Accessed: 12.04.2013

Kruse, Peter: Ein Kultobjekt wird abgewrackt. In: GDI Impuls. Wissensmagazin für Wirtschaft, Gesellschaft, Handel. 1/2009

Krust, Matthias: Daimler verschiebt Brennstoffzelle auf 2017, 20.1.2013. In: Automobilwoche online: http://www.automobilwoche.de/article/20130120/nachrichten/130119932#.UystdM5e7t1

Kurzweil, Peter: Brennstoffzellentechnik. 2nd Ed. Wiesbaden 2013

Lehr, Ulrike; Lutz, Christian; Pehnt, Martin: Volkswirtschaftliche Effekte der Energiewende: Erneuerbare Energien und Energieeffizienz. Osnabrück, Heidelberg 2012

Linde: Linde Technology 2/2003
Available at: http://www.the-linde-group.com/internet.global.thelindegroup.global/en/images/-Linde_Technology_2_2003_En14_9685.Pdf; Accessed: 12.02.2012

Linde: Linde study shows: Cost is not a big obstacle to hydrogen car infrastructure. 24.02.2005
Available at: http://www.hydrogenday.de/International/Web/Hydrogenday2005.nsf/240205_h2_-infrastrukturk_en.pdf; Accessed: 23.04.2013

Linz, Stefan; Touil, Sabine: Statistisches Bundesamt: Preise auf einen Blick. Wiesbaden Juni 2011
Available at: https://www.destatis.de/DE/Publikationen/Thematisch/Preise/Verbraucherpreise/-PreiseAufEinenBlick0170005107004.pdf?__blob=publicationFile; Accessed: 08.11.2015

Lund, Peter: Market transformation perspective and involvement of market actors and stakeholders in the IEA case studies. Prepared for "Technologies Require Markets" IEA Workshop on Best Practices and Lessons Learned in Energy Technology Deployment Policies Paris, 28-29.11.2001

Maibach, M; Schreyer, C.; Sutter, D.; van Essen, H.P. et. al.: Handbook on estimation of external costs in the transport sector. Internalisation Measures and Policies for All external Cost of Transport (IMPACT). Version 1.1. Delft, CE, 2008
Available at: http://ec.europa.eu/transport/themes/sustainable/doc/2008_costs_handbook.pdf; Accessed: 20.10.2012

Matic, Davor: Final Report. Study Group 5.3 Utilization of natural gas in transport sector. 24th World Gas Conference Argentina, 24.10.2009

McKinsey & Company on behalf of stakeholders from relating industries: A portfolio of power-trains for Europe: a fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles. Brussels 2010
Available at: http://www.iphe.net/docs/Resources/Power_trains_for_Europe.pdf; Accessed: 16.12.2011

Meiners, Jens: „Unsere Strategie ist richtig.“ „AI“ im Gespräch mit VW-Entwicklungsvorstand Dr. Ulrich Hackenberg. In: Automobil Industrie: Volume 54. Würzburg March 2009, p. 21

Meiners, Jens: „Wir sind im Angriffsmodus“. Die Produkt- und Technologieoffensive von Daimler ist in vollem Gang. Daimler-Entwicklungsvorstand Prof. Dr. Thomas Weber erklärt, was die Stuttgarter vorhaben. In: Automobil Industrie: Special OEM-Plattformen/Dezember 2012, p. 16

Mennekes: Elektromobilität. Product brochure. 2014

Menzen, Georg (BMWi): Übersicht zum NIP: Stand und Zukunft. Bundesministerium für Wirtschaft und Technologie. 13. Jahrestreffen des Netzwerks Brennstoffzelle und Wasserstoff NRW, 14. November 2013
Available at: http://www.brennstoffzelle-nrw.de/fileadmin/daten/jahrestreffen/2013/03_Menzen_-BMWi_NIP_NBW20131114.pdf; Accessed: 15.02.2014

Mock; Peter: EU vehicle technology study: Development of preliminary cost curves for the EU market. ICCT International Workshop on greenhouse gas reduction potential and costs of light-duty vehicle technologies. 27. April 2012
Available at: http://www.theicct.org/sites/default/files/ICCT_Apr27_ICCT_PM.pdf; Assessed: 24.02.2014

Mohrdieck, Christian; Veturi, Massimo, Breitrück, Katrin; Schulze, Herbert: In: Töpler, Johannes; Lehmann, Jochen: Wasserstoff und Brennstoffzelle; Technologien und Marktperspektiven. Berlin 2013

Morey, Bruce: Fuel cells return to focus. In: SAE international. 2013

Müller-Syring, Gert: Das Erdgasleitungsnetz als Katalysator für die Wasserstoffwirtschaft. Leipzig, 13. Januar 2010
Available at: http://wwwm.htwk-leipzig.de/~m6bast/rvlwasserstoff/100113neunteRIVLmsyring.pdf; Accessed: 08.11.2015

NHTSA, National Highway Traffic Safety Administration. U.S. Department of Transportation: Analysis of Published Hydrogen Vehicle Safety Research, DOT HS 811 267, Columbus, Ohio, February 2010
Available at: http://www.nhtsa.gov/DOT/NHTSA/NVS/Crashworthiness/Alternative%20Energy%-20Vehicle%20Systems%20Safety%20Research/811267.pdf, Accessed 08.11.2012

NPE, Nationale Plattform Elektromobilität*:* 2. Bericht Nationale Plattform Elektromobilität. Berlin 2011
Available at: http://www.bmvbs.de/cae/servlet/contentblob/66442/publicationFile/38143/zweiter-bericht-der-nationalen-plattform-elektromobiltaet.pdf; Accessed: 13.03.2012

NaturalHy*:* Preparing for the hydrogen economy by using the existing natural gas system as a catalyst. Final publishable activity report. SES6/CT/2004/502661. The Netherlands. March 2010

Neumann, Bernhard (TU Clausthal)***:*** Kapitel 5 Eigenschaften von Wasserstoff. 2007
Available at: http://www.iee.tu-clausthal.de/fileadmin/downloads/Scripte/W8830K5.pdf; Accessed: 09.11.2012

Nitsch, Joachim: *BMWi (Editor)****:*** Zweites Fachgespräch, Präsentation von Dr. Joachim Nitsch (DLR) zu "Bedeutung eines Klima- und Energieziels für den Verkehrssektor", 07.08.2012
Available at: http://www.bmvi.de/SharedDocs/DE/Anlage/UI-MKS/mks-referentenmaterialien-fachgespraech2-1.pdf?; Accesed: 25.022014

Olivier, Jos G.J.; Janssens-Maenhout, Greet; Peters, Jeroen A.H.W. (PBL Netherlands Environmental Assessment Agency)***:*** Trends in global CO_2 emissions. 2012 Report. The Hague. Bitthoven 2012
Available at: http://edgar.jrc.ec.europa.eu/CO2REPORT2012.pdf; Accessed: 26.03.2013

OPEC*:* World Oil Outlook 2007. Vienna, 2007
Available at: http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo_2007.pdf, Accessed: 08.11.2015

Parry, Ian W.H.; Darmstadter, Joel: Resources for the Future: The Costs of U.S. Oil Dependency. Discussion Paper 03–59. NW Washington, D.C., December 2003, p. 1

Pester, Wolfgang; Günnel, Thomas: Elektromobilität. Stadtbus mit Wasserstoff-Brennstoffzellen-Technik. 22.09.12 In: Automobil Industrie
Available at: http://www.automobil-industrie.vogel.de/antrieb/articles/379202/index2.html, Accessed: 06.102012

Peters, Dirk; Rumpke, Christian A.; Kalinowska, Dominika*:* dena: Erdgas und Biomethan im künftigen Kraftstoffmix. Handlungsbedarf und Lösungen für eine beschleunigte Etablierung im Verkehr. Aktualisierte Fassung, Berlin, September 2011
Available at: http://www.bdew.de/internet.nsf/id/D9A10360EC1648E6C1257A7D004E37A4/$file/-dena-Studie_Erdgas_und_Biomethan_im_kuenftigen_Kraftstoffmix.pdf; Accessed: 07.11.2012,

Pischinger Stefan: CO_2-Reduzierung: Neue zuverlässige und bezahlbare Lösungen am Motoren-Markt. Pressemitteilung Springer Verlag. 05.12.2013
Available at: http://www.springer.com/about+springer/media/pressreleases?SGWID=1-11002-6-1447541-0; Accessed: 10.01.2014

Plötz, Patrick; Gnann, Till; Kühn, André; Wietschel, Martin (Fraunhofer ISI): Markthochlaufszenarien für Elektrofahrzeuge. Langfassung. Studie im Auftrag der acatech – Deutsche Akademie der Technikwissenschaften und der Arbeitsgruppe 7 der Nationalen Plattform Elektromobilität (NPE). Karlsruhe, September 2013
Available at: http://www.isi.fraunhofer.de/isi-media/docs/e/de/publikationen/Fraunhofer-ISI-Markthochlaufszenarien-Elektrofahrzeuge-Langfassung.pdf; Accessed: 16.03.2014

Porter, Michael E.: Competitive Strategy – Techniques for Analyzing Industries and Competitors. New York 1980

PwC: The World in 2050. The accelerating shift of global economic power: challenges and opportunities, January 2011
Available at: https://www.pwc.com/gx/en/psrc/pdf/world_in_2050_jan2011.pdf; Accessed: 08.11.2015

Rivera-Tinoco, R.; Schoots, K.: Learning Curves for Solid Oxide Fuel Cells. In: Proceedings WHEC2010. Essen, 2010, Schriften des Forschungszentrums Jülich / Energy & Environment, Vol. 78-1, p. 263 - 272
Available at: http://juser.fz-juelich.de/record/135348/files/FC4_3_Rivera_Tinoco_rev0604.pdf; Accessed: 08.11.2015

Scheuerer, Klaus: BMW Group, Beauftragter des Vorstandes für Verkehr und Umwelt, Sprecher der Verkehrswirtschaftlichen Energiestrategie: Die Sicht der VES. Presentation at the Symposium of the Wasserstoff-Gesellschaft Hamburg e.V.: „Die Wasserstoff-Technologie in der Anwendung: Alternative Antriebstechnologien für die Mobilität des 21. Jahrhunderts“ at the Handelskammer Hamburg 21. Oktober 2008.

Schindler, Volker: Kraftstoffe Für Morgen. Eine Analyse von Zusammenhängen und Handlungsoptionen. Berlin, Heidelberg 1997

Schmidt, Klaus: Das große Miteinander. In Verkehrsrundschau, 1-2/2014, p. 20-21

Schott, Benjamin: Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg: Lithium – begehrter Rohstoff der Zukunft. Eine Verfügbarkeitsanalyse. Ulm, 08.06.2010
Available at: http://www.zsw-bw.de/infoportal/downloads/studien.html?eID=nfcmedialibrary&tx_nfc-medialibrary_pi1%5Buid%5D=1788&tx_nfcmedialibrary_pi1%5Bdownuid%5D=1788, Accessed: 08.11.2015

Schwarzer, M. Christoph: "Investitionen in Wasserstoff-Tankstellen werden sich auszahlen" Der Chef der Wasserstoff-Initiative NOW, Bonhoff, erklärt im Interview, wie der Aufbau der Infrastruktur finanziert wird. Öffentliche Mittel müssten später zurückfließen. In: Zeit-Online, 28.06.2012
Available at: http://www.zeit.de/auto/2012-06/wasserstoff-tankstellen-finanzierung; Accessed: 15.12.2013

Schwoon, Malte: Working Paper FNU-112. Learning-by-doing, Learning Spillovers and the Diffusion of Fuel Cell Vehicles, no year, Hamburg
Available at: https://www.fnu.zmaw.de/fileadmin/fnu-files/publication/working-papers/WP-FNU-112FCV_learning_by_doing.pdf; Accessed: 01.02.2013

Senatsverwaltung für Stadtentwicklung: Digitaler Umweltatlas Berlin, 07.02 Straßenverkehrslärm / 07.04 Schienenverkehrslärm (Issue 2005)
Available at: http://www.stadtentwicklung.berlin.de/umwelt/umweltatlas/karten/pdf/07_02_1_-2004.pdf; Accessed: 10.04.2013

SFK, Störfall-Kommission beim Bundesminister für Umwelt, Naturschutz und Reaktorsicherheit: Bericht Anwendung der Wasserstoff-Technologie. Eine Bestandsaufnahme des Arbeitskreises Wasserstofftechnologie. 2002
Available at: http://www.kas-bmu.de/publikationen/sfk/sfk_gs_37.pdf; Accessed: 04.11.2012

Shell Deutschland Oil GmbH: Shell PKW-Szenarien bis 2030. Fakten, Trends und Handlungsoptionen für nachhaltige Auto-Mobilität. Hamburg, 2009

Snyder, Kent (USABC): Overview and Progress of United States Advanced Battery Consortium (USABC) Activity. 15. May 2012
Available at: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2012/energy_-storage/es097_snyder_2012_o.pdf; Accessed: 12.04.2014

Statistisches Bundesamt: Preise. Verbraucherpreisindizes für Deutschland. Jahresbericht 2014. Wiesbaden 2015
Available at: https://www.destatis.de/DE/Publikationen/Thematisch/Preise/Verbraucherpreise/Ver-braucherpreisindexJahresberichtPDF_5611104.pdf?__blob=publicationFile; Accessed: 15.05.2015

Stephens-Romero, Shane; Brown, Tim; Samuelsen, Scott: STREET. Determining hydrogen filling station needs in targeted communities. Irvine, California, 13 July 2011
Available at: http://www.arb.ca.gov/fuels/altfuels/cf-outlets/meetings/uc%20irvine_street-_cfo%20workshop_13jul2011_final.pdf, Accessed: 17.10.2012

Stolzenburg, Klaus: Integration von Wind-Wasserstoff-Systemen in das Energiesystem: Zusammenfassung & Schlussfolgerungen. In: NOW-Conference: Integration von Wind-Wasserstoff-Systemen in das Energiesystem, 28. Jan. 2013, Berlin

StorHy: Hydrogen Storage Systems for Automotive Application. Project No.: 502667. Publishable Final Activity Report. 2008, 15.10.2008
Available at: www.storhy.net/pdf/StorHy_FinalPublActivityReport_FV.pdf; Accessed: 04.08.2012

T&E, European Federation for Transport and Environment. *Kågeson, Per:* Reducing CO_2 emissions from new cars - A progress report on the car industry's voluntary agreement and an assessment of the need for policy instruments: Brussels 2005
Available at: http://www.transportenvironment.org/docs/Publications/2005pubs/05-1_te_co2_cars.pdf, Accessed 30.03.2007

T&E, European Federation for Transport and Environment: EURO 5 and 6 emissions standards for cars and vans - Position Paper. Brussels, September 2006
Available at: http://www.transportenvironment.org/sites/te/files/media/2006%2009%20TE%20-Euro%205%20position.pdf, Accessed: 8.11.2015

Theodorou, Savvas C.; Florides, Georgios; Tassou, Savvas A.: The parameters used in multiple criteria decision making methodologies for drafting out renewable energy sources support schemes. In: World Renewable Energy Congress – Sweden, Linköping, 8–13 May 2011, p. 2619
Available at: http://www.ep.liu.se/ecp/057/vol10/ecp057vol10.pdf, Accessed: 8.11.2015

Total, Enertrag: Press Release: Pilotprojekt mit erneuer. Kraftstoff auf Berlins Straßen Freie Fahrt für die Energiewende: Wind-Wasserstoff erstmalig an der Tankstelle verfügbar. Berlin, 18. April 2012
Available at: http://www.presseportal.de/pm/25222/2236809; Accessed: 08.11.2015

Tübke, J.; Berger, T.; Krampfert, M.: Sicherheitsbetrachtungen verschiedener Batterietypen, Workshop Forum Elektromobilität 24.07.2013

UN DESA: United Nations. Dep. of Economic and Social Affairs. Population Division. World Population Prospects. New York 2005

UN DESA: United Nations. Department of Economic and Social Affairs. Population Division: World Population Prospects. The 2006 Revision. Highlights. New York 2007
Available at: http://www.un.org/esa/population/publications/wpp2006/WPP2006Highlights_rev.pdf, Accessed: 11.03.2008

UN DESA: United Nations. Department of Economic and Social Affairs. Population Division: World Population Prospects. The 2010 Revision. Highlights. New York 2011

UN/ECE: Regelung Nr. 101 der Wirtschaftskommission der Vereinten Nationen für Europa (UN/ECE). Einheitliche Bedingungen für die Genehmigung der Personenkraftwagen, die nur mit einem Verbrennungsmotor oder mit Hybrid-Elektro-Antrieb betrieben werden, hinsichtlich der Messung der Kohlendioxidemission und des Kraftstoffverbrauchs und/oder der Messung des Stromverbrauchs und der elektrischen Reichweite sowie der nur mit Elektroantrieb betriebenen Fahrzeuge der Klassen M1 und N1 hinsichtlich der Messung des Stromverbrauchs und der elektrischen Reichweite. In: Amtsblatt der Europäischen Union. L138/1, 26.05.2012

UNEP: The Emissions Gap Report 2012. A UNEP Synthesis Report. Exec. Summary. Nairobi 2012
Available at: http://www.unep.org/pdf/2012gapreport.pdf; Accessed: 08.11.2015

Unruh, D.; Rohde, M.; Schaub, G.; Universität Karlsruhe (TH): Fischer-Tropsch Synthese von Kohlenwasserstoffen ausgehend von Biomasse – In-situ H_2O-Abscheidung und Verbesserung der Kohlenstoff-Nutzung. FVS Fachtagung 2003
Available at: http://www.fvee.de/fileadmin/publikationen/Workshopbaende/ws2003-2/ws2003-2_04_04.pdf; Accessed: 02.03.2014

U.S. Congress: Joint Economic Committee: Chairman Jim Saxton (R-NJ): OPEC and the High Price of Oil. Washington DC, November 2005

VDE, Verband der Elektrotechnik, Elektronik, Informationstechnik (VDE): VDE-Trendreport 2014. Schwerpunkt Smart Cities. Elektro- und Informationstechnik. Innovationen – Märkte – Nachwuchs. Frankfurt, April 2014

VDMA, Verband Deutscher Maschinen und Anlagenbau. *Working Group Fuel Cells*: Innovative Fuel Cell Technologies from Germany on the Verge of Serial Production. Members Directory. 2014
Available at: http://www.vdma.org/documents/266669/906967/Herstellerverzeichnis-AG-Brennstoff-zellen-2014-04.pdf/d98b9247-d7b0-4df7-8246-d009993dd18d, Accessed: 30.08.2014

VES, Verkehrswirtschaftliche Energiestrategie: Eine gemeinsame Initiative von Politik und Wirtschaft. 2. Statusbericht der Task Force an das Steering Committee, Berlin 21.06.2001

VES, Verkehrswirtschaftliche Energiestrategie: Eine gemeinsame Initiative von Politik und Wirtschaft. 3. Statusbericht der Task Force an das Steering Committee, Berlin August 2007

Viswanathan, B.; Helen, M.: Is Nafion®, the only Choice? In: Bulletin of the Catalysis Society of India, 6 (2007) 50-66

WBCSD, World Business Council for Sustainable Development: Mobility 2030: Meeting the challenges to sustainability – The sustainability Project, Full Report, 2004

Welke, Jörg: Wasserstoff Akzeptanz und Vertrauen. Auf dem Weg in die Wasserstoffgesellschaft. Marktplatz Zulieferer, Presentation at the NOW event „Marktplatz und Zuieferer“. Weinheim, 22.10.2012

Wenske, Michael (Enertrag): Wasserstoff – Herstellung per Elektrolyse. Vortrag an der FH Stralsund. No year.

Westfalen: Überall für alles da: Mobile Systeme für die Gasversorgung. Product Brochure. No year. Available at: http://www.westfalen-ag.de/fileadmin/user_uploads/Westfalen_AG/Technische_Gase/Allgemein/Prospekte_Technische_Gase/Mobile_Systeme_fuer_die_Gaseversorgung.pdf; Accessed: 25.12.2012

Williamson, Ian: Air Products on behalf of the H_2Mobility Consortium: H_2-Mobility – Towards commercialisation of Fuel cell vehicles. Presentation to US HTAC. 3rd June 2010
Available at: http://www.hydrogen.energy.gov/pdfs/4_williamson_0610.pdf; Accessed: 23.05.2011

Wolf, Enno; Zerres, Christopher; Zerres, Michael: Delphi Technik. No year
Available at: http://www.studium-ratgeber.de/delphi-methode.php, Accessed: 09.05.2008

Wolf, Joachim (Linde Gas): Die neuen Entwicklungen der Technik. Presentation at: Medienforum Deutscher Wasserstofftag. 2003

World Bank: Turn Down the Heat. A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics. Potsdam June 2013
Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/14000/9781464800559s.pdf?sequence=6; Assessed: 08.11.2015

WSS, Deutscher Wasserstoffspiegel: WSS is published by the DVGW six times a year. http://www.dwv-info.de/aktuelles/haupt_wspiegel.html. Reference is given to the concrete issue: WSS Issue/Year

Zaidi, Javaid: Research Trends in Polymer Electrolyte Membranes for PEMFC. In: Zaidi, Javaid; Matsuura, Takeshi (Ed.): Polymer Membranes for Fuel Cells. New York August 2009

Zalosh, Robert: Blast waves and fireballs generated by hydrogen fuel tank rupture during fire exposure. In: Proceedings of the 5th International Seminar on Fire and Explosion Hazards, Edinburgh, UK, 23-27 April 2007, p. 149-158

Zero Regio: Lombardia & Rhein-Main towards Zero Emission: Development and Demonstration of Infrastructure Systems for Hydrogen as an Alternative Motor Fuel Instrument Integrated Project. Report to Deliverable D 5.3: Analysis communication concept 700-bar refuelling. 2006

ZSW: Press Release 04/2014, 15.04.2014
Available at: http://www.zsw-bw.de/uploads/media/pi04-2014-ZSW-StandElektromobilitaetweltweit-neu.pdf; Accessed: 16.08.2014