On the Exploration of German Mitigation Scenarios

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Summary

The decisive mitigation of greenhouse gas emissions in order to avoid dangerous anthropogenic interference with the global climate system constitutes one of the greatest challenges of the 21st century. Germany is being observed by the global community on its unprecedented quest for decoupling a highly industrialized country's economy from CO_2 emissions and has ambitious long-term mitigation targets. Due to the complex challenge of transforming Germany's energy system, political actors frequently demand scientific expertise in the form of long-term, model-based mitigation scenarios. However, existing mitigation scenarios for Germany suffer from severe methodological shortcomings and are highly intransparent on their implicit normative assumptions. This is not reconcilable with the good principles for the science-policy interface. Thus, the guiding theme of this thesis is to explore how implicit normative considerations in model-based mitigation scenarios can be made explicit.

The first part of this thesis conducts an exploratory research that intends to overcome the current limitations in model-based mitigation scenario development by applying a collaborative scenario definition and evaluation process engaging civil society stakeholders. Taking an analytical-deliberative approach to participation, civil society stakeholders from the transport and electricity sector frame the definition of boundary conditions for the hybrid energy-economy model REMIND-D and evaluated the resulting scenarios with regard to plausibility and socio-political implications. The developed mitigation scenarios for Germany achieve 85% CO_2 emission reduction in 2050 relative to 1990. However, the scenario evaluation unravels that the technological solutions to the mitigation problem proposed by the model give rise to significant societal and political implications that deem at least as challenging as the mere engineering aspects of low-carbon technologies. These insights underline the importance of comprehending mitigation of energy-related CO_2 emissions as a socio-technical transition embedded in a political context. The second part of this thesis explores alternative German mitigation scenarios for identifying what kinds of energy strategies for transforming the German electricity sector towards high shares of renewable electricity generation (RES-E) they embody and under which premises they are viable. It performs a comparative meta-analysis of ten model-based mitigation scenarios from six recent publications, including those developed in the first part of the thesis. The scenarios group into three different energy strategies that exploit the basic options of increasing RES-E shares (domestic RES-E production, energy efficiency improvements and RES-E imports) to a different extent. Substantial behavioral, institutional and engineering barriers to implementation that apply to all suggested energy strategies are identified. Upon investigating the reasons why the different scenario projections diverge, it turns out that they are in many cases based on expert judgments rather than resulting from numerical modeling. These involve normative judgments and need to be made more explicit in future research.

In sum, this thesis reveals in exploratory research that the realization of a collaborative mitigation scenario definition and evaluation process, as a means to address normative considerations in model-based mitigation scenarios explicitly, is possible in small scale and scope. Hence, the primary message for future research is that such a participatory process should be repeated in the form of a more comprehensive assessment of German mitigation scenarios, which requires refined participatory methods so as to keep transaction costs within boundaries. It is commendable to adapt the elaborated methods developed in the literature on inclusive risk governance, which extensively deals with the questions of whom to include in a discourse, for what reasons and by means of which methods.

Zusammenfassung

Die maßgebliche Reduktion von Treibhausgasemissionen zur Vermeidung von gefährlichen anthropogenen Störungen des Klimasystems stellt eine der größten Herausforderungen des 21. Jahrhunderts dar. Deutschland wird bei seinem Bestreben als hochindustrialisiertes Land sein volkswirtschaftliches Wachstum von CO_2 Emissionen zu entkoppeln von der Weltgemeinschaft aufmerksam verfolgt. Auf Grund der komplexen Herausforderung die die Transformation des deutschen Energiesystems darstellt, besteht seitens der politischen Akteure eine Nachfrage nach langfristigen, modellbasierten Klimaschutzszenarien. Allerdings leiden existierende Klimaschutzszenarien unter schwerwiegenden methodologischen Limitationen und sind zudem sehr intransparent bezüglich ihrer impliziten normativen Annahmen. Dies lässt sich nicht mit der guten Prinzipien von wissenschaftlicher Politikberatung vereinen. Daher ist das Leitthema dieser Dissertation zu explorieren wie implizite normative Abwägungen in modellbasieren Klimaschutzszenarien explizit gemacht werden können.

Der erste Teil dieser Dissertation führt eine Explorationsforschung durch, die die heutigen Limitationen von Klimaschutzszenarien zu überwinden intendiert indem ein kollaborativer Prozess zur Definition und Evaluation von Klimaschutzszenarien angewandt wird welcher zivilgesellschaftliche Stakeholder einbindet. Mittels eines analytisch-deliberativen Ansatzes zur Partizipation gestalten zivil-gesellschaftliche Stakeholder aus dem Transport- und Elektrizitätssektor die Definition der Rahmenbedingung für das hybride Ökonomie-Energie Modell REMIND-D und evaluieren die daraus resultierenden Szenarien bezüglich ihrer Plausibilität und sozio-politischer Implikationen. Die entwickelten Klimaschutzszenarien erreichen eine Minderung der CO_2 Emissionen von 85% im Jahr 2050 gegenüber 1990. Jedoch zeigt sich bei der Evaluation der Szenarien, dass die technologischen Lösungen zur Vermeidung von CO_2 Emissionen wie sie das Modell vorschlägt signifikante gesellschaftliche und politische Implikationen zur Folge hat, welche sich als mindestens so große Herausforderung wie die rein ingenieurstechnischen Aspekte von kohlenstoffarmen Technologien darstellen. Diese Einsichten unterstrichen die Wichtigkeit die Vermeidung von energiebedingten CO_2 Emissionen als sozio-technische Transition die in einen politischen Kontext eingebettet ist zu begreifen. Der zweite Teil dieser Dissertation exploriert alternative Klimaschutzszenarien um zu identifizieren welche Energiestrategien zur Transformation des deutschen Elektrizitätssektors hin zu hohen Anteilen von erneuerbaren Energien (EE) sie verkörpern und unter welchen Prämissen sie realisierbar sind. Es wird eine komparative Meta-Analyse von zehn modellbasierten Klimaschutzszenarien durchgeführt, welche sechs aktuellen Publikationen entnommen sind, einschließlich der Szenarien aus dem ersten Teil dieser Dissertation. Die Szenarien lassen sich in drei Gruppen einteilen, die die grundsätzlichen Optionen zur Erhöhung des Anteils von EE im Stromsektor (Erhöhung der inländischen EE-Produktion, Reduktion der Nachfrage durch Energieeffizienzmaßnahmen, Import von EE-Strom) in unterschiedlichen Maßen ausschöpfen. Es werden substanzielle Hürden zur Implementierung der Energiestrategien identifiziert die sich auf Verhaltensweisen, Institutionen und ingenieurstechnische Aspekte beziehen. Bei der Erforschung der Gründe warum sich die Projektionen der Szenarien unterscheiden stellt sich heraus, dass diese in vielen Fällen auf Expertenurteilen beruhen anstatt aus numerischer Modellierung zu resultieren. Diese sind mit normativen Werturteilen verbunden und müssen in zukünftiger Forschung expliziter gemacht werden.

Zusammenfassend zeigt diese Dissertation in einer Explorationsforschung, dass die Verwirklichung eines kollaborativen Prozesses zur Definition und Evaluation von Klimaschutzszenarien, als Mittel um normative Abwägungen in modellbasierten Klimaschutzszenarien explizit zu adressieren, in geringer

Größenordnung und mit limitiertem Umfang möglich ist. Daher ist die primäre Botschaft für zukünftige Forschung, dass solch ein partizipativer Prozess in Form eines umfangreicheren „Assessments“ von deutschen Klimaschutzszenarien wiederholt werden sollte, welches verbesserter partizipativer Methoden bedarf um die Transaktionskosten im Rahmen zu halten. Es empfiehlt sich dafür auf die elaborierten Methoden zurückzugreifen die in der Literatur über „Inclusive Risk Governance“ entwickelt worden sind, die sich extensiv mit den Fragen beschäftigt wer in einen Diskurs einbezogen werden soll, aus welchen Gründen und mittels welcher Methoden.

Chapter 1

Introduction

The decisive mitigation of greenhouse gas emissions in order to avoid dangerous anthropogenic interference with the global climate system constitutes one of the greatest challenges of the 21st century. The question of how much an individual nation should mitigate emissions, particularly energy-related carbon dioxide, and by which means is at its heart a political question, involving bargaining, negotiation and compromise. Due to the complex challenge of transforming a nation's energy system towards a low-carbon future, political actors frequently demand scientific expertise in the form of long-term, model-based mitigation scenarios as guiding input to the political discussion.

Model-based mitigation scenarios depict individual transformation pathways from the sheer infinite space of possible futures. They essentially constitute complex analytical thought experiments converting a wide range of input assumptions into projections of future developments of key variables in the energy system. Currently, mitigation scenarios predominantly focus on proposing portfolios of low-carbon technologies for the different sectors of the energy system. The underlying models root in engineering approaches to energy system modeling and stand in a tradition of providing factual knowledge. Yet, by selecting specific means to the policy end of mitigation, mitigation scenarios inherently rely on normative assertions to justify the choice. Since science does not have the mandate to determine the desirable course of action for society, it is problematic if mitigation scenarios' normative assumptions are (i) not made transparent, (ii) hidden behind seemingly factual statements and (iii) defined by science alone. To the author's knowledge these criteria apply to all existing long-term, model-based mitigation scenarios for Germany. Since the German Government aims at very ambitious mitigation targets but the German energy policy arena still discusses the appropriate policy means controversially thereby demanding and relying on scientific advice, there is a clear need for mitigation scenarios that adhere to the good principles of the science-policy interface.

The guiding theme of this thesis is thus to explore how implicit normative considerations in model-based mitigation scenarios can be made explicit. More specifically, this thesis deals with the exploration of German mitigation scenarios in two ways: First, it conducts an exploratory research that intends to overcome the abovementioned limitations in model-based mitigation scenario development by applying a collaborative scenario definition and evaluation process engaging civil society stakeholders, taking an analytical-deliberative approach. Second, it explores alternative German mitigation scenarios for identifying what kinds of energy strategies for transforming the German electricity sector towards high shares of renewable electricity generation they embody and under which premises they are viable.

Before the concise objectives and the outline of this thesis are presented in Section 1.5, the following provides a more comprehensive outline of the problem setting. Section 1.1 recapitulates the global context, motivating the need for ambitious mitigation efforts. Section 1.2 gives brief background information on the history and status quo of the energy transition in Germany. Section 1.3 discusses methodological limitations of existing German mitigation scenarios and proposes potential remedies. Section 1.4 provides the theoretical foundation of this thesis by drawing on a normative model of the science-policy interface with regard to mitigation scenario development.

1.1. Why Ambitious Mitigation Efforts?

The fundamental problem in climate change is that increases in the atmospheric concentration of long-lived greenhouse gases (GHGs) alter the energy balance of the climate system (IPCC, 2007b, p.5). The most important GHGs that induce a global warming effect are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Their atmospheric concentrations have risen considerably as a result of human activities since entering the industrial age (from 1750 onwards), mainly due to fossil energy consumption and shifts in land-use patterns. The already incurred increase in global mean temperature (GMT) between 1850–1899 and 2001–2005 amounts to 0.76°; a continuation of recent trends in GHG emissions may lead to an increase of GMT of up to 6°C until the end of the century, versus 1989-1999 levels (IPCC, 2007b). The risks associated with an increase in GMT are diverse (IPCC, 2007a; Smith et al., 2009), ranging from risks to unique and threatened systems, e.g. increased damage or irreversible loss of systems such as coral reefs, tropical glaciers, endangered species, biodiversity hotspots and small island states to extreme weather events such as heat waves, droughts, floods, wildfires or tropical cyclones. Also, large-scale components of the earth system may alter their qualitative state under global warming (Lenton et al., 2008), including arctic summer sea-ice loss, melting of the Greenland ice shield, dieback of the amazon rainforest and chaotic changes in the Indian Summer Monsoon.

In the year 1992, 154 nation states have signed the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro. Its primary objective as stated in §2 is to "achieve […] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system […] within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." (United Nations, 1992, p. 4). To date, 194 nation states and the European Union have ratified the treaty (UNFCCC, 2012). The 15th Conference of the Parties in 2009 resulted in the Copenhagen Accord, which specifies the UNFCCC's objective in that the increase in global mean temperature shall remain below 2°C as compared to pre-industrial levels and reconfirms "strong political will to urgently combat climate change in accordance with the principles of common but differentiated responsibilities and respective capabilities" (UNFCCC, 2009, p.5). However, instead of a agreeing on a second commitment period for the Kyoto protocol, which specified legally binding GHG emission targets for developed countries, individual countries submitted voluntary mitigation pledges for the year 2020. Figure 1 illustrates how the range of the Copenhagen pledges is inconsistent with GHG emission levels that are likely to keep to the 2°C target.

More ambitious domestic mitigation pledges as well as their realization are required in order to achieve the articulated objective of the UNFCCC. This is valid both for the short term and long term development of GHG emissions. In fact, the window of opportunity for stabilizing GHG concentrations in the atmosphere at levels that allow for a likely chance to keep the politically defined 2°C target is urging for timely action. There is scientific consensus that such an emissions trajectory requires global GHG emissions to peak before 2020 and decrease substantially thereafter (Fisher et al., 2007).

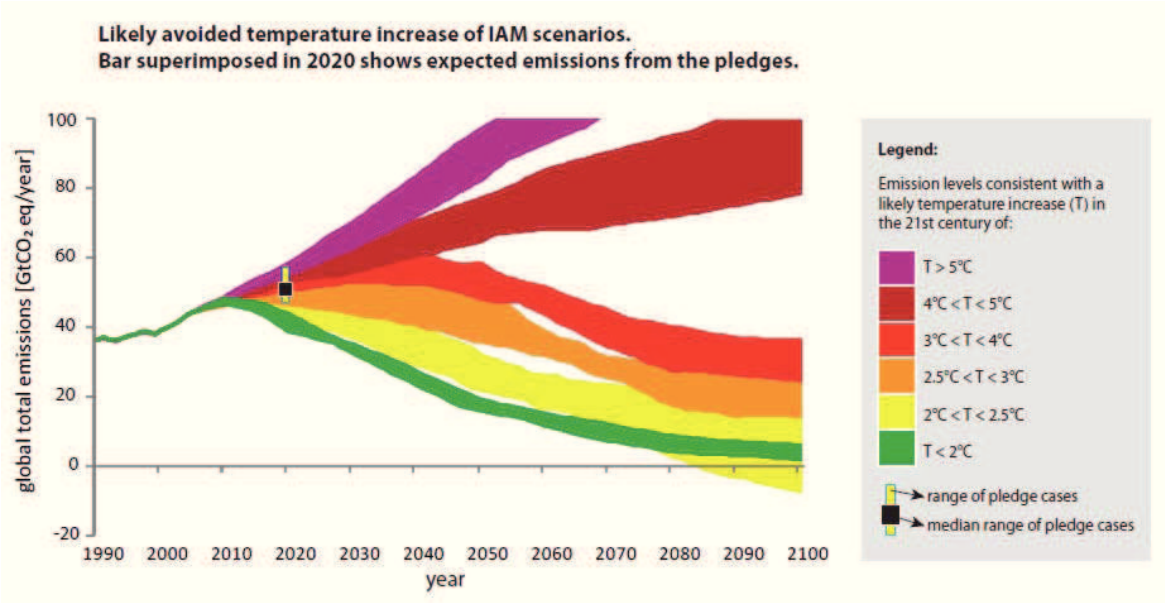

Figure 1. Copenhagen pledges to reduce GHG emissions, in comparison to emission trajectories and corresponding projected increases in global mean temperature over the 21st century. Source: UNEP (2010, p. 10).

CO_2 constitutes the most important anthropogenic GHG; its concentration has risen from a pre-industrial value of around 280 ppm to 379 ppm in 2005 (IPCC, 2007b) and 394 ppm in 2012 (NOAA, 2012). The primary source of global CO_2 emissions has been and still is the combustion of fossil resources, which as of today constitutes the backbone of the global economy. Coal, oil and gas jointly supplied 81.4% of total global primary energy demand in 2008 (IEA, 2010). For CO_2 emissions to peak in the near term, the global energy system will need to undergo a deep, structural transformation. Energy systems are characterized by highly planning- and capital-intensive assets with technical lifetimes of up to several decades, so significant lead times are required for investments into new infrastructure and energy conversion technologies. In the meantime, existing fossil-fuel based existing infrastructure will continue to emit. The International Energy Agency has quantified the estimated CO_2 emissions from existing energy system infrastructure and concludes: “The door towards 2°C is closing - will we be locked in?” (IEA, 2011). Whether or not humankind will ultimately keep a foot in the door depends on future international efforts to mitigate GHG emissions, especially CO_2.

1.2. The German Energy Transition – A Brief History

Germany is being observed by the global community on its unprecedented quest for decoupling a highly industrialized country’s economy from CO_2 emissions. Until 2011 it achieved a 21% decrease in CO_2 emissions relative to 1990 (BMWi, 2012). Also, Germany is recognized for its tremendous increase in the share renewable electricity generation from 5% of domestic electricity production in 1990 to 20% in 2011 (BMU, 2012b). Yet, the plans of the German Government go much further: In 2010, it released a

long-term strategy for Germany's future energy provision, the "Energy Concept", which aims at a CO_2 emission reduction target of 80-95% until 2050 relative to 1990 (Federal Government, 2010). The undertaking has been coined as the "Energy transition – future made in Germany" (BMU, 2010) and intends to stimulate the largest infrastructure project of the coming decades (Bim in Lippert, 2012). An important element is the transformation of the electricity system towards high shares of renewable electricity generation, which is manifested in §1(2) of the Renewable Energy Sources Act: It defines minimum targets of 50%, 65% and 80% in 2030, 2040 and 2050, respectively. However, as the President of the Association of German Chambers of Industry and Commerce puts it: "regarding the German energy transition, nothing is resolved but the targets" (Neuerer, 2012, p.1).

In order to grasp the present dynamics in German energy politics and policy, it is worthwhile to briefly recapitulate their historical context. Since World War 2, Western Germany's energy policy has experienced distinct phases that differ with respect to the dominant objectives and technology focus (Czakainski, 1993; Brauch, 1997), as well as the type of involved and affected actors and the type of general, underlying consensus on energy supply (Lippert, 2012). During the 1950s, while reconstructing Germany, the main objective has been economic efficiency and domestic lignite and hard coal constituted the most important primary energy sources. In the 1960s, increased competition between coal and cheap oil as well as natural gas led to protective energy policy for domestic hard coal mining. Energy policy increasingly adopted the objective of import independence and public R&D investments in nuclear energy increased substantially, leading to the emergence of a nuclear industry. In the 1950s and 60s, a cooperative, "practiced" energy consensus bonded the few involved actors, confined to the Federal and State Governments, as well as the coal and nuclear industry, underpinned by sectorial consensus in the form of protective coal policies and nuclear support (Lippert, 2012).

During the 1970s, with the global oil crises and public mass protest against nuclear energy in Germany, security of supply and social sustainability moved into the focus of energy policy. The public played an increasingly important role by openly questioning the sustainability of a coal and nuclear based energy supply. This tendency manifested in the 1980s in the form of a huge public debate on forest dieback supposedly associated with coal electrification. Environmental protection moved towards a central objective of energy policy, as further signified by establishing a Federal Ministry for the Environment, Nature Conservation and Nuclear Safety in 1986, five weeks after the Tschernobyl nuclear disaster. In fact, Tschernobyl gave the final impetus for the already crumbling energy consensus of earlier decades to break in its decisive elements (Schmidt-Preuß, 1995). Public protests against the peaceful use of nuclear energy substantiated and the political process slowly steered towards negotiating a nuclear phase-out. At the same time, climate protection was placed high on the political agenda, additive to the historically accumulated energy policy objectives of security of supply, social sustainability and environmental protection. In 1988, the final report of the Enquête Commission "Preventive Measures to Protect the Earth's Atmosphere", commissioned by the German Parliament, was released – even before the first assessment report of the IPCC. It indicated that an increase of GMT of 1-2°C was on the one hand unavoidable, and on the other hand the maximum acceptable increase. There was a high consensus across political parties that climate protection should be a central topic in energy policy, however, there was no consensus on *how* this should be achieved (Watanabe, 2011) .

In 1990 the rapid reunification of East and West Germany altered political priorities and distracted public attention from environmental and climate issues (Watanabe, 2011). Major financial transfers were targeted at measures to reconstruct the eastern German energy sector, including subsidies for the energy-efficient renovation of old building stock, replacement of lignite-based residential heating with gas furnaces, and a replacement of the majority of power plants including the decommissioning of highly inefficient lignite plants (Müller, 1998). These developments, at least partly driven by climate policy measures (Schleich et al., 2001), had a visible impact on the structure of Germany's fossil primary energy demand as well as total CO_2 emissions from the energy sector, see Figure 4. Between 1990 and 1995, lignite consumption decreased by more than one third, while natural gas consumption increased continuously. CO_2 emissions declined throughout this time period, encouraging German politics to take a leading role in international climate policy. Berlin hosted the first UNFCCC Conference of the Parties in 1995, where Chancellor Kohl announced an ambitious CO_2 emission reduction target of 25% in 2005 relative to 1990. However, looking at the data ex-post, the speed of energy-related CO_2 emission reduction decreased after the reunification period and only 20% have been reached as late as 2010.

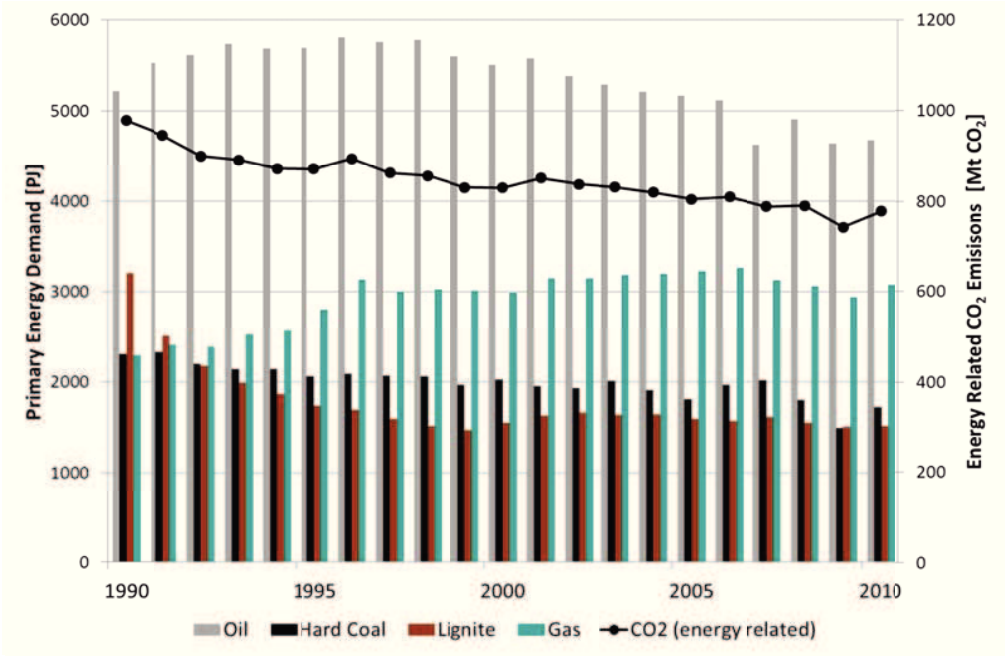

Figure 1. German fossil primary energy demand and energy-related CO2 emissions from 1990 to 2010. Own illustration based on data from BMWi (2012).

The political debate on appropriate policy measures for mitigation is ongoing, with the German energy and climate policy arena split in two camps until this day: an "economic prosperity coalition" and an "environmental protection coalition" (Watanabe, 2011). While they essentially share the vision of a low carbon economy, they are not sharing the same vision of how this ought to be achieved, e.g. which technologies should play a major role and what kind of policy instruments to adopt. After 16 years of the economic prosperity coalition in power under Chancellor Kohl, the environmental protection coalition gained significantly more influence with the 1998 federal elections won by the social democrats and forming a coalition with the greens, a party that originated in the civil anti-nuclear movement.

They rapidly introduced several energy policy changes: First, they pushed through a long-debated ecological tax reform in 1999. The continuous decrease in crude oil consumption over the past decade, see Figure 4, may partly be attributed to the eco tax – heating oil demand for households decreased from levels fluctuating around 900 PJ until 2000 to below 600 PJ in 2011 and petrol demand decreased from a previously stable level of around 1300 PJ to 800 PJ in 2010 (BMWi, 2012). Yet, the actual steering effect of the ecological tax reform remains disputed (Watanabe, 2011). Second, the new Government intended to settle the decade-old conflict on the use of nuclear power by imposing a change in legislation that paved the way for a nuclear phase-out until 2022. And third, in 2000, they reformed legislation on renewable energy sources (RES) support by means of the Renewable Energy Act in 2000, a feed-in tariff scheme that guarantees primary feed-in and fixed remunerations schemes for 20 years for electricity generation from renewable energy sources. As becomes evident by Figure 5, the share of RES in total electricity demand increased significantly in response, from 5% in 2000 to 20% in 2011. While the Renewable Energy Act received much merit for initial market formation for renewable technologies (Jacobsson and Lauber, 2006; Wüstenhagen and Bilharz, 2006), it is heavily criticized for economic inefficiency (Frondel et al., 2010) and subject to ongoing debate. Another amendment in 2012 is awaited.

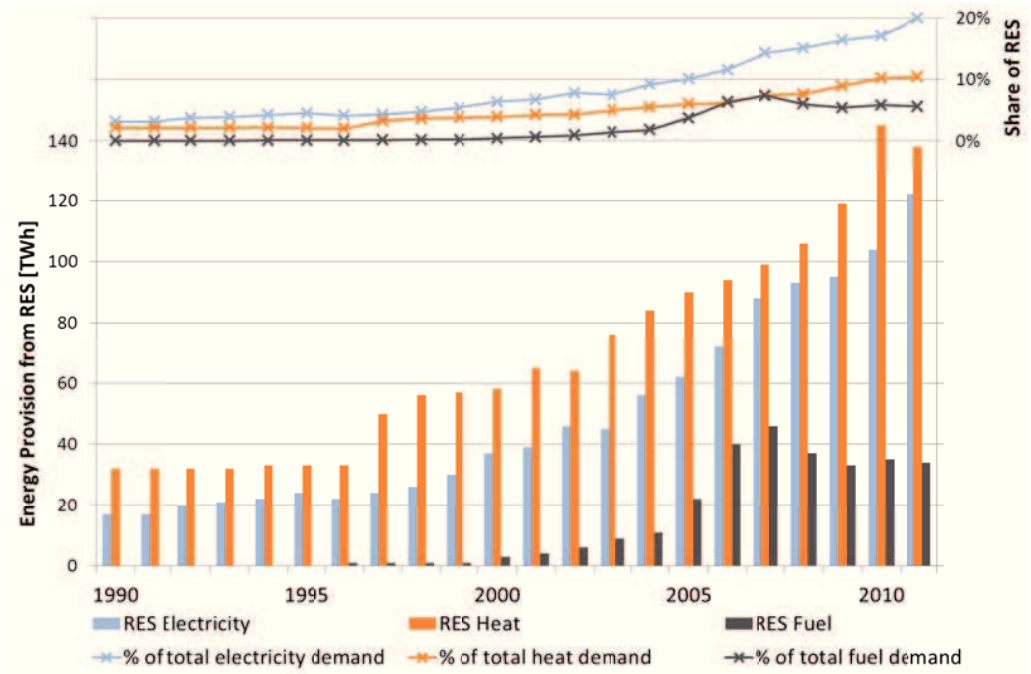

Figure 2. Energy production from renewable energy sources (RES), in the electricity, heat and fuel sector both in absolute terms and as a share in total sectorial demand. Own illustration based on data from BMU (2012).

The share of RES in heat and fuel provision also increased over the last decade, largely based on biomass technologies in both sectors. European legislation triggered these developments. The directive 2003/30/EG required a minimum share of 5.75% of biofuels or other RES based fuels in domestic markets. After overshooting the target, Germany has kept the constant minimum share since 2009. In 2009, the European legislation was strengthened and directive 2009/28/EG prescribes different binding

targets for each member states' RES shares in final energy demand for 2020. Upon non-attainment, sanctions can be imposed. Germany hence committed to advance from its share of 12.2% RES in final energy demand in 2011 (BMU, 2012a) to 18% in 2020. In order to translate this into domestic policy, a RES heat subsidy program was implemented in 2009 with the Renewable Heat Act and the amended Biofuel Quota Act. However, particularly the introduction of biofuels is opposed by the German public manifested in refusal to use petrol with 10% biofuel additive (E10) which endangers Germany's fulfillment of the biofuel quota (MWV, 2011).

Summarizing, the objective of CO_2 mitigation has gradually advanced on the priority list of German energy policy over the past three decades and now enjoys top priority next to the historical objectives of security of supply, social sustainability and environmental protection other than climate protection. While some progress is already achieved, the ambitious targets set by the Government are still far out of reach and RES shares are required to increase significantly in all energy system sectors over the coming decades. With an increasing deployment of RES technologies, the amount of involved and affected actors in the energy policy process increases dramatically. This is both due to spatially distributed RES technologies and concomitant infrastructure requirements constituting a new form of land use that alters German landscapes and energy service consumers being involved in low-carbon solutions, which require alternative end-use appliances or shifting modes of energy consumption. Thus, in order to enable the energy transition as a profound change process, the interests of a wide range of affected parties need to be accommodated so as to allow for the deployment and implementation of low-carbon solutions that are not impeded by acts of refusal of individual parties. The call for social acceptance of renewable energies (Wüstenhagen et al., 2007) has become a keyword in the German energy policy arena. Often, it is understood as something that can be established ex-post to investment or policy decisions by providing sufficient information to the public (e.g. Federal Government, 2010). However, attempts to explain acceptance and opposition increasingly resorts to procedural and institutional factors like perceived fairness and levels of trust (Devine-Wright, 2008). Rayner (2010) argues that the process of how a society chooses an energy future itself is as important for a socially, politically, economically and environmentally sustainable outcome as the availability of low-carbon technologies.

The Ethics Commission for a Safe Energy Supply, installed by Chancellor Merkel in 2011, calls for a basic consensus on the basis and future of prosperity, the idea of progress, the willingness to take risks and the safety to be achieved as a basic requirement for changing the energy supply structure (Ethics Commission for a Safe Energy Supply, 2011). It further emphasizes that "the energy transition will only succeed through a collective effort spanning all levels of politics, business and society" (p. 5). However, currently, the German energy policy arena is characterized by a multitude of conflicts on what kinds of policy measures for incentivizing mitigation are appropriate and which technology solutions are desirable. Because of the long planning horizon and the long lifetimes of energy system technologies the course for the state of the energy system in several decades needs to be set now. Due to the complexity of the challenge, several political actors have demanded scientific expertise in the form of long-term, model-based mitigation scenarios as guidance in the energy policy debate. These scenarios are frequently put forward as a scientifically sound discussion basis; however, in fact they suffer from severe methodological limitations as will be outlined in the following section.

1.3. Methodological Limitations of Existing German Mitigation Scenarios and Potential Remedies

For evaluating the scientific quality of mitigation scenarios two criteria are of special importance. First, the analytical quality of the underlying model: Is it based on sound theory? Does it represent the pivotal features of the modeled system? Second, the input assumptions: Are they plausible? Who determined the input assumptions? To date, there are three studies presenting mitigation scenarios for the German energy system which are based on quantitative energy system models and are consistent with the Government's mitigation target of 80-95% CO_2 emission reduction in 2050 relative to 1990. They were all commissioned by political actors as indicated by Table 1, which additionally summarizes their applied models, problem statements and the imposed policy targets.

Table 1. Salient features of existing long-term, model based and ambitious mitigation scenarios for Germany that cover all sectors of the energy system, i.e. heat, transport and electricity.

Publication and Sponsor	Models	Problem Statement	Targets
"Model Germany" (WWF, 2009), commissioned by the World Wildlife Fund Germany	• Bottom-up demand model(Prognos) • Dispatch model (Prognos)	"What can and needs to happen technologically and how do associated policies look like?" (p.1)	95% GHG emission reduction in 2050 relative to 1990.
"Energy Scenarios for an Energy Concept of the Federal Government" (EWI/GWS/Prognos, 2010), commissioned by the Federal Ministry of Economics and Technology	• Bottom-up demand model (Prognos) • Dispatch model (DIME) • Macro-econometric model (Panta Rhei)	"Which technical measures that reduce energy demand and GHG emissions are suitable for reaching the targets?" (p.2)	40% / 85% CO_2 emission reduction in 2020 /2050 relative to 1990, ≥ 18% share of RES in final energy demand in 2020, ≥ 50% RES in primary energy supply in 2050
"Long Term Scenarios and Strategies for the Expansion of Renewable Energies in Germany under the Consideration of Developments in Europe and Globally" (DLR/IWES/IFNE, 2010; 2012), commissioned by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety	• Spreadsheet models (SZENAR, ARES) • Simulation model German electricity sector (SimEE) • Optimization model European electricity sector (REMix)	Describe a self-consistent quantity framework of the expansion of renewable energies; derive and discuss the structural and economic effects of this expansion.	80% CO_2 emission reduction in 2050 relative to 1990, RES-E share ≥ 50% / 65% / 80% in 2030 / 2040 / 2050; in one scenario also 100% RES-E share in 2050

To start with the analytical quality of the underlying models one needs to note first, that all studies apply several partial models which are soft-linked in order to jointly cover all sectors of the energy system and, if applicable, macroeconomic dynamics. An advantage of soft-coupling numerically intensive partial models is that more technological or sectorial detail can be covered, as opposed to an integrated model of the energy system and macro economy. Soft-linking, however, eliminates the potential for feedback effects since the exchange of data between two or more models yields seemingly

deterministic model input for the respective other model(s). Two important aspects in modeling energy system developments are whether investment decisions, reflected in capacity additions of available technologies, are modeled endogenously or imposed as exogenous assumption and how the larger economic development in terms of GDP growth is treated.

WWF (2009) applies several models of the Prognos AG: A detailed bottom-up energy demand model, consisting of a variety of sectorial sub-modules that generate differentiated projections of the energy demands of the industry and the residential and commercial sectors, and a high-resolution power plant model (p. 12). The demand model relies on an exogenously imposed GDP projection as a driving input variable. One of the outputs of the demand model is the annual electricity demand, along with its load profile. An exogenously determined deployment path of renewable electricity generation (RES-E) capacities, along with exogenously set full load hours, yields a RES-E feed-in profile, which is subtracted from the annual electricity demand load profile on an hourly basis (p. 18). The resulting residual load is an input to the power plant model of the Prognos AG, which determines the technology mix of conventional electricity generation technologies; their selection is based on maximizing their rate of return on equity (p.18). Thus, the model setup falls into the category “bottom-up simulation” and by construction excludes feedback effects of energy sector development on both GDP growth and RES-E investments. For reaching the ambitious target of 95% GHG emission reduction in 2050, relative to 1990, a strong focus is put on demand-side policies.

The EWI/GWS/Prognos (2010) study, commissioned by the Federal Ministry for Economics and Technology (BMWi) takes a very similar approach and soft-couples the bottom up energy demand model of the Prognos AG, the European electricity market model DIME (Dispatch and Investment Model for Electricity Markets in Europe) and the macro-econometric model Panta Rhei. The differentiated sectorial final energy demand is provided by the demand model of Prognos. The resulting electricity demand for Germany serves as an input to DIME, which is a dynamic optimization model that determines the cost-minimal coverage of European electricity demand, considering the technical and economic parameters, by simulating the future power plant dispatch. The deployment path of RES-E capacities is apparently exogenous to DIME, as “the scenario construction of the electricity generation sector is further based on a model of renewable energies in Europe that represents several RES-E technologies in a regionally differentiated manner” EWI/GWS/Prognos (2010, p. 28). More detail on how precisely the deployment path of RES-E is obtained is not provided. Results of both the Prognos demand model and DIME serve as an exogenous input to Panta Rhei, which then determines direct and indirect macroeconomic effects, i.e. GDP projections. However, there is no iterative feedback of information from the Panta Rhei model to the demand model or DIME. The resulting GDP paths are very similar to the one imposed to the demand model at the outset. Again, the model setup falls into the category “bottom-up simulation”.

Finally, the study DLR/IWES/IFNE (2010) and its successor DLR/IWES/IFNE (2012), commissioned by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), primarily relies on the simulation tool ARES for determining a ‘quantity framework’ for a ‘realistic’ development path of renewable energy technologies (p.1). The term ‘realistic’ is defined the sense that existing energy policy ‘action possibilities’ and instruments, structural barriers and friction losses are considered, and

deployment paths of renewable energy technologies are not unrealistically ambitious. The market development of individual renewable energy technologies is an exogenous input to ARES. It is stated that "the capacity deployment path of RES-E technologies results from an extrapolation of the historical dynamics, under the assumption of priority feed-in for RES-E until 2050" (DLR/IWES/IFNE, 2010, p. 46). The RES-E capacity deployment path is validated for selected scenarios and years in a dynamic simulation with the soft-coupled models SimEE of IWES and REMix of DLR. This, however, does not replace an endogenous representation of systemic effects. As before, the core model setup is a "bottom-up" simulation.

A common denominator of these "bottom-up" modeling approaches is that their analytical quality leaves substantial room for improvement. The investment dynamics in innovative technologies are determined exogenously and are based on expert opinion rather than resulting from numerical optimization. This has deep implications as the resulting scenarios are essentially normative projections, which is not indicated transparently next to their presentation in the scenario reports. Also, important systemic effects are not taken into account endogenously. Further, there exists no underlying theory for "bottom-up" models. Rather, they take on an engineer's perspective by incorporating detailed descriptions of technologies while assuming market adoption of the most efficient technologies (Hourcade and Robinson, 1996). It is further postulated that current market forces do not operate perfectly and an efficiency gap exists between the current technology penetration and best available techniques. Suggested mitigation policy implications are to remove barriers to adoption of the best available technique. In the global energy system models literature, "bottom-up" models have been found to be highly optimistic regarding the technical mitigation potential, due to picking "low-hanging fruits" which are in fact not picked today (Grubb et al., 1993; Hourcade and Robinson, 1996). Economists argue that the postulated malfunctioning of market forces is only apparent and can be explained by complexity and heterogeneity of consumer preferences as well as hidden costs, e.g. information costs or perceived risks associated with capital costs (Hourcade and Robinson, 1996). On the contrary, in calibrated "top-down" models, this complex set of behavioral factors is captured in price and income elasticities. This alternative approach to modeling energy systems adopts an economic perspective, often at the cost of technological detail, but allowing for an integrated analysis with feedback mechanisms between economic and technological development and endogenous representations of technological change. An important aspect is that such models are backed by economic theory and hence have an analytical foundation.

In global energy system modeling, hybrid approaches have become increasingly popular, exemplified by e.g. the models REMIND-R (Leimbach et al., 2010), WITCH (Bosetti et al., 2006) or IMACLIM-R (Crassous et al., 2006). Such hybrid models contain both representations of the economy and a "bottom-up" energy supply model representing individual energy carriers and conversion technologies. Hybrid models reconcile the advantages of both concepts, i.e. the technological detail of "bottom-up" models and the endogenous representation of behavioral factors by means of price and income elasticities. Economic theory suggests different approaches to numerical modeling, the most popular being growth models, derived from macroeconomic theory, and computable general equilibrium (CGE) models, rooted in microeconomic theory. Both types of models solve an optimization problem, which is,

however, formulated in a different manner. CGE models explicitly consider different economic agents that maximize their respective objective function. The model solves for each time step by determining the market prices for which markets clear and are in a state of general equilibrium. An advantage of this approach is the representation of rich economic detail with individual economic agents, distribution effects and the possibility to include policy instruments explicitly. The major disadvantage of CGE models is the lack of intertemporal efficiency, as the model is solved recursively for each time step. For macroeconomic growth models, advantages and disadvantages are vice versa.

The most prominent macroeconomic growth model is the Ramsey-Cass-Koopmans model (Ramsey, 1928; Cass, 1965; Koopmans, 1965). It belongs to a class of economic models rooted in the theory of welfare economics, which is also referred to as normative economics. Normative economics addresses questions about what should be done in a particular set of circumstances and is founded in utilitarian ethics (Perman et al., 2003). Utility is a term introduced by early utilitarian writers (David Hume, Jeremy Bentham and John Stuart Mill) that refers to the individual's pleasure or happiness. Welfare is then some aggregation of individual utilities. Being a consequentialist theory, utilitarians postulate that actions which increase welfare are right and actions that decrease welfare are wrong, in a normative sense (Perman et al., 2003). Following from this moral judgment framework, the objective function of macroeconomic growth models is to maximize an intertemporal social welfare function. In the Ramsey-Cass-Koopmans model, social welfare is defined as the present value of logarithmic per capita consumption over the time span of analysis. Consumption is determined via a macroeconomic production function that considers the production factors capital and labor in the classical model, and additionally energy when applied to hybrid energy-economy modeling. Given the side constraints to the optimization problem, maximizing the social welfare function yields an intertemporally optimal solution that would have been picked by a benevolent social planner. Thus, scenarios produced from growth models are intertemporally optimal and also referred to as "first-best solution", "benchmark solution", or "best-case reference". The particular notion of optimality applied here is that the optimization results are Pareto efficient, meaning that nobody could be better off without somebody else being worse off. Drawing on the second fundamental theorem of welfare economics, the social planner solution is equal to the decentralized market solution under conditions of perfect competition. The Ramsey-Cass-Koopmans model applied in energy scenarios has been particularly criticized on ethical grounds for the practice of pure time discounting, which assumes that consumption today is valued more than consumption in the future. This is not reconcilable with the ethical principle of intergenerational equity. Also, it has been criticized that defining social welfare exclusively in terms of per capita consumption is an inadequate representation for environmental economic problem settings (Perman et al., 2003).

To summarize, adopting a theory-based economic perspective on modeling energy systems is also not limitation-free and its analytical quality depends primarily on how well the model is calibrated to the system under analysis. Here, the major challenge is data scarcity and measurement problems as the determination of price and income elasticities are problematic. Given that the hybrid approach to energy system modeling can reveal important insights on optimal and sartorially integrated transition pathways it appears worthwhile to develop such a model for Germany.

Having sketched the alternatives approaches to energy system modeling, one crucial issue remains: The necessary input assumptions for projecting future developments. As has been revealed in the discussion above, the largest part of the scenario projections in the existing studies for Germany constitute exogenous assumptions. Thus, the scenario projections are in fact input assumptions which are chosen by the modelers on a normative basis; however, the studies refrain from providing both a transparent motivation and a detailed reporting of input assumptions. This impedes an evaluation of their plausibility. Scenario projections are nevertheless reported in a very technical and factual manner, thereby hiding implicit value judgments. Since science does not have the mandate to determine the desirable course of action for society this practice is problematic, and especially so if the mitigation scenarios serve as policy advice. Potential remedies for this limitation include a transparent reporting of all input assumptions used in mitigation scenario development and an explicit indication of assumptions that are based on normative considerations. Furthermore, those scenario assumptions involving value judgments are ideally not determined by science alone but are at best obtained in a public debate as the following elucidates.

1.4. A Normative Model of the Science-Policy Interface

The conceptual interplay between science and the policymaker has spurred a long-standing debate in the political and philosophical literature. The basic problem at stake is: Who should define the policy ends and who should decide on adequate policy means to attain these ends? For the focal issue of this thesis, domestic mitigation scenarios for Germany, the question translates into: Who should define a German mitigation target? Who should decide on the policy means that are implemented to attain this target? The conceptual answers to these questions depend on which normative model of science-policy interface is adopted and influence the ideal methodology for developing domestic mitigation scenarios.

Habermas (1971) provides a seminal description of three conceptual models for the science-policy interface that prevail to date. These are the ‘decisionist’, ‘technocratic’ and ‘pragmatic’ model. In simplified terms, the decisionist model assumes that policy ends are set by legitimized policymakers alone, as they reflect inherent value judgments about desirable futures. Science provides the most effective means to attain these ends in a value-free, rational and objective manner. The technocratic model on the other hand supposes that the policy problem is too complex to be conceived without expert knowledge and both policy ends and means need to be provided by science. The role of the policymaker is then restricted to implementing the policy measures determined by scientists in the form of rational, absolutely objective knowledge. In both models, the public is not involved in the policy process. Essentially, the existing mitigation scenarios for Germany presented in the preceding Section are examples of scientific results developed under the decisionist paradigm as they adopt the mitigation targets determined by the German Government and report policy means in a seemingly factual manner.

As outlined by Edenhofer and Kowarsch (2012), the crucial assumption of both the decisionist and technocratic model – that science can possibly deliver rational, objective and value-free knowledge – is flawed. The main argument shattering the fact/value dichotomy on philosophical grounds is that

scientific judgments presuppose epistemic values for the generation of scientific knowledge (Putnam, 2002). Such epistemic values include perceptions of concepts like coherence, quantification, plausibility, robustness or predictive capacity, i.e. drawing normative judgments on how science ought to reason. Thus, scientific knowledge is inevitably value-laden. Coming back to the German mitigation scenarios, one needs to acknowledge that their propositions on the future portfolio of technology solutions for the German energy system hinge on the scientists' understanding of e.g. a coherent energy system model, plausible input assumptions and robust findings. Will domestic mitigation scenarios thus necessarily constitute value-laden expert judgments and as such be ill-suited for providing scientific advice on mitigation policy?

Edenhofer and Kowarsch (2012) reconcile this issue by drawing on the ideas of philosophical pragmatism and develop the pragmatic-enlightened model (PEM) of science-policy interface, an amended version of the pragmatic model. The notion of pragmatism employed for deriving the conceptual model is in the tradition of American philosophers John Dewey and Hilary Putnam. It postulates that although scientific judgments imply values, they can nevertheless be "objective" in a pragmatist sense if they are the result of a thorough inquiry which has established their repeated practical usefulness for solving a problematic situation. The pattern of Deweyan inquiry (Dewey, 1938) as a set of operations by which a problematic situation is resolved consists of five steps: First, a problematic situation is noticed, followed by the second step of a thorough analysis and framing of the problem and the identification of concrete solutions, termed "ends-in-view". In a third step, one develops means to attain the identified ends-in-view. Fourth, the possible ends-in-view/means combinations are scrutinized and for their direct and indirect consequences. Fifth, after a implementing the selected means, they are evaluated to determine the lessons-learned for the next inquiry. The PEM suggested by Edenhofer and Kowarsch (2012) applies the pattern of Deweyan inquiry to the science-policy interface, as illustrated in Figure 7.

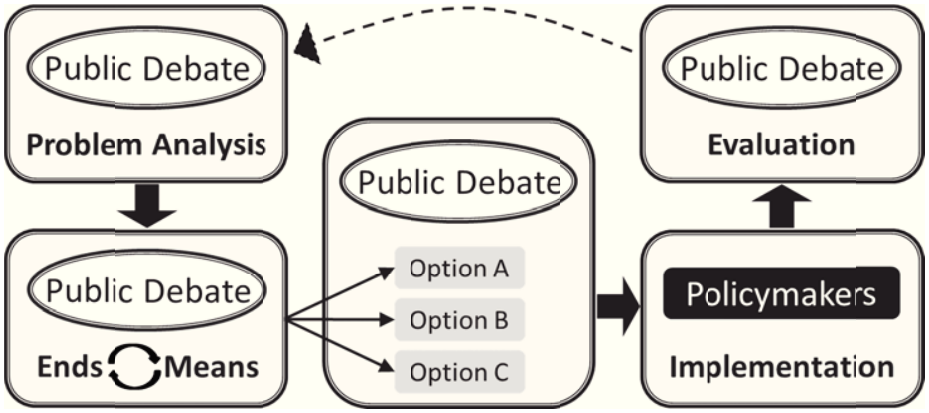

Figure 3. The process of scientific policy advice as suggested by the pragmatic-enlightened model (PEM). Source: Edenhofer and Kowarsch (2012), Figure 4.

The type of public debate considered by the PEM does not intend to include every single citizen, but rather forms according to the functional requirements of the respective situation. Ideally, all parties that

are required to identify, analyze and frame the problematic situation, are able to contribute possible means to solve it, have a stake in its solution and are potentially affected by direct or indirect consequences of policy means should be part of the public debate in the different stages of the PEM process. Due to the complexity and significant transaction costs of operationalizing such a dialogue, it is suggested to primarily engage representatives of the stakeholder groups. Furthermore, essential participants in the public debate are policymakers and science.

According to Edenhofer and Kowarsch (2012) the role of science in the public debate is that of a facilitator, stimulator and advisor; taking advantage of its elaborated methods. In the first stage of the PEM, science can analyze and criticize the problem framing that policymakers and stakeholders discuss before policymakers decide on ends-in-view. In the context of climate policy, this implies assessing the problematic impacts of climate change and discussing means to cope with it, such as mitigating emissions by deploying RES technologies and adopting RES targets. Given that impacts of climate change are global while mitigation measures and targets are introduced on a national level, global and domestic considerations are clearly interdependent. Thus, there should be both a global PEM assessment cycle and a nested national PEM assessment cycle that considers a nation's mitigation targets and means such as domestic RES targets in the broader context. It is important to note that the mitigation target of 80-95% CO_2 emission reduction in 2050 relative to 1990 articulated by the German Government constitutes such an end-in-view. From a PEM perspective it is now important to scrutinize possible means for achieving this end-in-view and their direct and indirect consequences, which constitutes the second stage of the PEM process.

Here, the role of science is especially vital for assessing possible ends-in-view/means combinations, i.e. mitigation scenarios for the case at hand, given a high transparency of scientific assumptions and methods, value judgments and uncertainties. Also, the interests and preferences of affected parties need to be taken into account in order not to overlook possible societally relevant means or means-consequences. For Germany, this pivotal step of the PEM process is yet outstanding, as the discussion above has shown that the existing mitigation scenarios do not satisfy the transparency criteria. As it is impossible for science to explore all possible ends-in-view/means combinations in the third stage of the PEM process, Edenhofer and Kowarsch (2012) suggest scrutinizing a selection in detail for their possible consequences, in close cooperation with policymakers and stakeholders in a public debate. Here, it is of particular importance to include all those scientific disciplines which are necessary to provide a comprehensive picture of the direct and indirect consequences of the analyzed ends-in-view/means combinations. Thus, the important task of science in this stage is to "make policy options more explicit, including their main conditions as well as (normative or other) premises under which these policy options are viable and reasonable" (Edenhofer and Kowarsch, 2012, p. 20). Finally, in the fourth stage, science can contribute by rigorously monitoring the outcomes of the process and record lessons learned for improved performance in future assessments of the policy problem.

To date, no such comprehensive PEM-guided assessment has been pursued for the problem of CO_2 emission mitigation in a rigorous manner, neither on global nor on national scale. There are at least two convincing reasons why the PEM as a normative model of the science-policy interface is advantageous: First, on a conceptual level it supports the ideals of democracy and its application to the mitigation

policy process could lead to more democratic, transparent and fair decisions. Second, on a practical level an application of a PEM-guided assessment is likely to lead to more intelligent policy outcomes that have a high chance of being realized as their possible consequences have been assessed and negotiated ex-ante. Particularly for the policy problem of mitigation it is of essential importance to draw on the knowledge stock held by those who are directly and indirectly affected by conceivable policy means. Here, the lead times from decision making to deployment of low-carbon solutions are particularly long-stretched due to energy system assets being highly planning- and capital-intensive. Moreover, the energy system is highly interdependent and non-realization of one element of the system can easily lead to underperformance or malfunctioning of the system as a whole. For example, if power grid extensions that are bottlenecks for ensuring security of electricity supply are impeded due to local protest by individual communities, this may adversely affect the successful transition of the German electricity towards high shares of renewables as a whole. Given that the door towards stabilizing GHG emissions is closing, it is of utmost importance to develop policy ends and means combinations that have a high chance of being realized without effective resistance of individual actors who suffer from direct or indirect consequences of policy measures and have been ignored in the negotiating process, i.e. policy means that enjoy a high level of social acceptance. However, the successful realization of a PEM-guided assessment for the policy problem of German mitigation presents itself as a formidable challenge due to the complexity of the task of engaging science, society and policymakers in a cooperative dialogue.

1.5. Objectives and Outline

Having sketched the urge for ambitious mitigation efforts, the demand for mitigation scenarios in the German energy policy arena, the severe limitations of existing literature on the topic as well as potential analytical and conceptual remedies, it unfolds that this thesis strives to explore how German mitigation scenarios that adhere to the good principles of the science-policy interface can be developed in practice. This objective corresponds to realizing an elaboration of possible ends-in-view/means combinations in a public debate as suggested by stage two of the PEM (Edenhofer and Kowarsch, 2012). In more specific terms this objective translates into the engagement of civil society stakeholders in the development and evaluation of model-based mitigation scenarios for Germany that explore how the end-in-view of 85% CO_2 emission reduction in 2050 relative to 1990 as articulated by the German Government (Federal Government, 2010) can be achieved, given the normative considerations of civil society stakeholders. Taking the policy process proposed by the PEM one stage further, a second objective of this thesis is to explore alternative German mitigation scenarios for identifying what kinds of energy strategies they embody as well as making the premises under which they are viable more explicit. The scope of the second objective is confined to the electricity sector, whose transition towards high shares of electricity generation from renewable energy sources constitutes an important pillar of German mitigation ambitions. The contributions of this thesis thus comprise both methodological advancements in terms of how to apply a PEM-guided assessment in practice as well insights on how the German energy transition can be enabled. Figure 4 visualizes the two objectives of this thesis in relation to the PEM as its theoretical foundation.

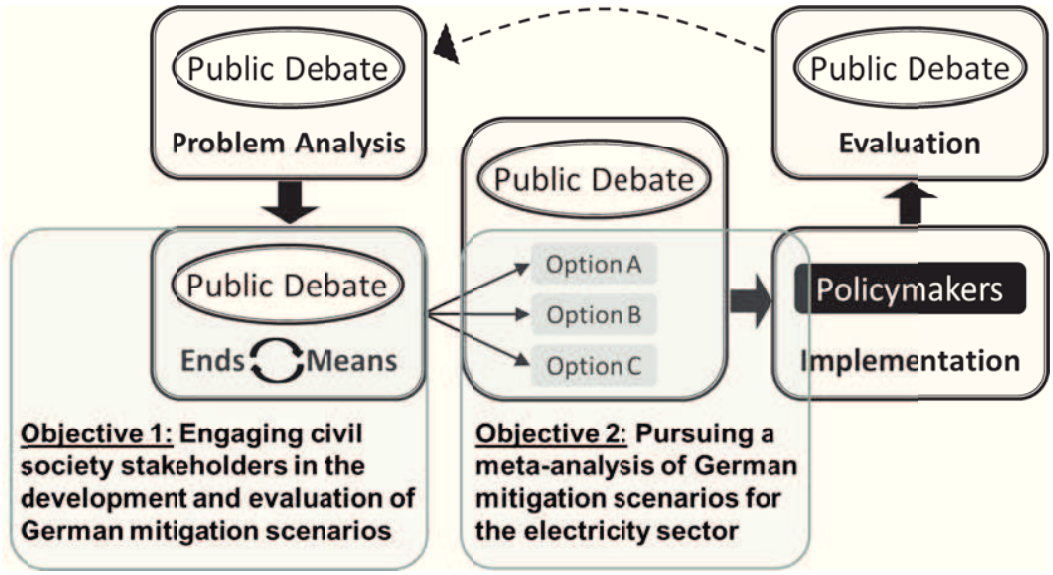

Figure 4. Objectives of this thesis in relation to its theoretical foundation, the pragmatic-enlightened model (PEM) of the science-policy interface. Source: Own illustration and Edenhofer and Kowarsch (2012), Figure 4.

This thesis is structured in two parts along the lines of the objectives. The first part constitutes an exploratory research that aims at developing model-based mitigation scenarios in collaboration with civil society stakeholders, taking an analytical-deliberative approach (Stern and Fineberg, 1996; Renn, 1999) in which deliberation frames analysis and analysis informs deliberation. The underlying idea is that civil society stakeholders frame the scenario definition according to their preferences and evaluate the scenario results derived with an energy system model for Germany in an iterative process. The following sets of research questions arise:

- **What kind of organizational project design is suitable to engage civil society stakeholders in mitigation scenario development? How can stakeholder preferences frame the definition of model-based mitigation scenarios?**

- **Which mitigation scenarios for Germany emerge from the exploratory research and how are they evaluated? What are the key findings for enabling the German energy transition?**

The second part of the thesis pursues a comparative meta-analysis of selected German mitigation scenarios for the electricity sector and deals with the following research questions:

- **What kinds of energy strategies for transforming the German electricity sector towards a high share of renewable electricity generation are embodied by selected mitigation scenarios for Germany? Which barriers to implementation can be identified? What are reasons for diverging scenario projections?**

The outline of this thesis is as follows: In order to realize a collaborative scenario definition and evaluation process, necessary prerequisites are first a functional project design and second an energy system model for Germany. **Chapter 2** proposes an innovative project design blueprint that can serve as a starting point for the methodology of future collaborative mitigation scenario exercises. As regards the energy system model, it has been outlined above that there exists currently no model for Germany that is based on sound economic theory. In order to fill this gap, the hybrid energy-economy model REMIND-D has been developed in the course of this research. In order to provide full transparency, **Chapter 3** provides a detailed documentation of the model structure, the input data used to calibrate the model to the Federal Republic of Germany and the techno-economic parameters of the technologies considered in the energy system module. With the project design and the energy system model at hand, the collaborative scenario definition and evaluation process is conducted with a number of German civil society stakeholders. **Chapter 4** presents the outcomes of the stakeholder dialogues and the resulting German mitigation scenarios obtained with REMIND-D, as well as the civil society stakeholders' evaluation of the mitigation scenarios. Addressing the second objective of this thesis, Chapter 5 pursues a comparative meta-analysis of selected German mitigation scenarios for the electricity sector, including two of the scenarios developed in Chapter 4. It investigates a number of strategic questions relevant for the long-term transformation of the German electricity sector towards high shares of electricity generation from renewable energy sources and groups the scenarios according to the energy strategy they embody. Furthermore, **Chapter 5** identifies barriers to implementations that are applicable to all identified energy strategies and explores the reasons for diverging scenario projections. Finally, **Chapter 6** summarizes the findings of the core chapters in this thesis by answering the research questions posed above and concludes this exploration of German mitigation scenarios with suggestions for future research.

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Chapter 2

Social Acceptance in Quantitative Low Carbon Scenarios

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Social Acceptance in Quantitative Low Carbon Scenarios

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Introduction

Significant reductions of global greenhouse gas emissions play a key role in addressing the problem of dangerous anthropogenic climate change. In order to achieve low-stabilization targets, emissions have to peak before 2020 (UNEP 2010). Yet, greenhouse gas mitigation is a challenge for which no simple and single recipe exists, as exemplified by the abortive developments of international negotiations and limited mitigation success since the ratification of the Kyoto protocol. The dominant source of greenhouse gas emissions, especially CO_2, is the anthropogenic use of fossil resources for energy supply. Consequently, mitigation requires a long-term transformation towards low carbon energy systems. To date, the majority of research efforts on how to achieve this have concentrated on identifying innovative technological solutions and assessing optimal deployment pathways, as well as suitable policies in the different sectors of the energy system. This tendency manifests itself in the predominantly model-based low carbon energy roadmaps published recently, e.g. the "Lead Study" in Germany (Nitsch et al. 2010) or on the European level the EU Roadmap 2050 (European Commission 2011a). Central topics are aggregate assumptions on the developments of energy demand, energy efficiency, investment costs of future technologies, technical potentials, demographic structures, etc., that serve as an input or are an output of the respective quantitative energy system model frameworks. However, sociological dimensions, in particular the social acceptance of implications of the suggested energy futures, are rarely addressed. This is a serious shortcoming, as the transformation of national energy systems represents a profound and long-term change process involving society as a whole. Moreover, a high level of unacceptability could result in group's refusal of climate measures or in avoidance strategies that would then decrease its potential efficiency; the question of "social acceptability" is also one of relative unacceptability and its consequences.

In the context of energy system strategies, social acceptance has three dimensions (Wüstenhagen 2007): (i) socio-political acceptance, referring to the acceptance of technologies and policies by the public, key stakeholders and policy makers, (ii) community acceptance of site-specific local projects and (iii) market acceptance, referring to the process of consumers' and investors' adoption of innovative low-emission products. For addressing

these dimensions in the context of energy system transformation scenarios, it is necessary to extend the engineering/economics toolbox of research methods towards truly interdisciplinary approaches by combining them with methodology developed in other strands of social science and the humanities. One implication is to not only rely on quantitative methods, but also on qualitative methods, that are useful when the specific individual perspective of the research subject is focused upon, the research subject has been poorly investigated so far and verbal data is to be interpreted (Bortz & Döring 1995); all of these issues apply in the present context.

One approach to address social acceptance in low carbon scenarios to is to include well-managed and repetitive stakeholder consultations as an integrative part of an energy system model scenario definition process. The parameters and input variables of the aggregated model are carefully translated into tangible, real-life, implications for the public and then evaluated by civil society representatives with respect to their social acceptance. The considerations emerging from these stakeholder consultations are translated back into configurations of technical model parameters, i.e. political framework conditions, and result in different low carbon energy system scenarios. These integrated scenarios are calculated by the quantitative models and the results are again translated into tangible meaning and presented to the civil society stakeholders, emphasizing at least the first of the three dimensions of social acceptance in energy system strategies. Such a collaborative scenario definition process has been undertaken together by non-governmental organizations (NGOs) and research institutes within the EU-project ENCI LowCarb (Engaging Civil Society in Low Carbon Scenarios) for France and Germany. Based on the ENCI LowCarb experience, this paper proposes a pragmatic project design blueprint, intending to foster repetitive collaboration between civil society and science for introducing dimensions of social acceptance into model-based, low carbon energy system scenarios.

Section 2 presents the existing barriers to interdisciplinary research and collaboration processes between science and civil society in the context of energy system scenarios. Section 3 introduces a conceptual project design blueprint intended to overcome these difficulties. It describes four distinct phases of a collaborative scenario definition process. Section 4 elaborates on the specific experiences from the ENCI LowCarb project and problems encountered during the process. Section 5 reflects on limitations and compares to other scenario projects involving stakeholders. Section 6 concludes.

Barriers to Collaboration

In order to derive a project design that encourages collaboration between engineering, economics and other strands of social science as well as civil society, it is worthwhile to step back and analyse why comprehensive collaborative projects between scientific disciplines and civil society are to date rare, especially in the field of energy system scenarios. Three general observations are helpful. First, one has to acknowledge that "science" and "civil society" are umbrella terms for communities that again consist of a large variety of distinct sub-communities. Second, these communities and sub-communities are distinct with respect to their raison d'être, objectives and culture, i.e. values, norms and language. Third, they have a tendency to coexist, in the sense that there are few institutional intersections per se; collaborative projects across communities are often preceded by proactive, innovative, and open-minded individuals.

Civil Society and Non-Governmental Organizations

Civil society is a rather vague umbrella term, Reverter-Bañón (2006) argues that her understanding of civil society is three-fold: as associational life (Putnam, cited in Reverter-Bañón 2006), as good society, and as public sphere (Habermas, cited in Reverter-Bañón 2006). In more concrete terms, the World Bank (2004) defines the notion as follows: "The term civil society refers to the wide array of non-governmental and not-for-profit organizations that have a presence in public life, expressing the interests and values of their members or others, based on ethical, cultural, political, scientific, religious or philanthropic considerations. Civil society organizations (CSOs) therefore refer to a wide array of organizations: community groups, non-governmental organizations (NGOs), labor unions, indigenous groups, charitable organizations, faith-based organizations, professional associations, and foundations". CSOs are formed as people with similar interests organize themselves and represent a certain set of claims, beliefs, norms and values. Often, the term CSO and NGO are conflated. Willets (2002) defines the term NGO as an independent voluntary association of people acting together on a continuous basis and for some common purpose. In this paper, CSO is used as the umbrella term and NGOs are considered as a subset of CSOs.

Many CSOs intend to change the status quo of a certain affair; environmental NGOs lobby for reducing pollution, churches preach humanitarian values and citizens' initiatives fight for local projects. Often,

CSO activists operate at the grass-roots level and are ideal-driven. In terms of climate change mitigation, environmental NGOs have played a visible role with projects focused on greenhouse gas emission reduction involving lobbying, campaigning or protesting against specific local affairs. With the intention to scientifically back up their lobbying work, NGOs have increasingly been seeking contact to the scientific communities. Moreover, many environmental NGOs have shifted from constituting an activist movement towards more mature organizations employing scientists that did not want to continue a purely academic career. NGOs have published comprehensive scientific studies to underpin their claims and objectives with research results, e.g. WWF (2008; 2009) and Greenpeace (2007). However, these studies were largely commissioned to research institutions and prepared in principal-agent relationships more than in structured collaboration processes. In sum, it appears natural to foster collaboration between NGOs, rooted in the civil society community, and scientists as a starting point for incorporating social acceptance into energy system scenarios. In later steps, CSO representatives are included in the collaboration process.

Scientific Cultures and Mitigation

In terms of public attention and academic outreach visibility, the mitigation problem has mainly spurred natural scientists and engineers to develop and assess low-emission technologies, system scientists to perform integrated analyses of optimal deployment paths, and economists to analyse energy market forces and suitable policies. Politically prominent theoretical research results on long-term mitigation strategies have been obtained by engineering or economic methods: mathematical modelling, optimization, game theory, statistics and econometrics, i.e. quantitative methods. Maybe this is due to the seductive charm of hard numbers and associated "scientific facts". Yet, a recent publication of the German Academies of Sciences strongly encourages collaborations between engineers, natural and cultural scientists, as they consider this a prerequisite for achieving ambitious climate policy targets in Germany (Renn 2011). Within the social science literature, the refusal, acceptance, or avoidance strategies of actors regarding mitigation measures is less investigated. There are efforts to understand the public and local acceptance of renewable energies by means of specific case studies, e.g. Zoellner, Schweizer-Ries and Wemheuer (2008), Musall and Kuik (2011) and Nadaï (2007), involving qualitative interviews and questionnaire-based survey analysis. However, there are to date no visible efforts to combining these findings with purely quantitative energy/

economics models. One possible explanation is the coexistence of the different scientific sub-communities.

Even within different scientific disciplines, there are many coexisting and often conflicting strands of research. Many of the conflicts root from methodological issues. Albeit scholars of both the quantitative and the qualitative tradition share the overarching goal of producing valid descriptive and causal inferences (Brady & Collier, cited in Mahoney & Goertz 2006), there are substantial discrepancies in basic assumptions and practices. Schrodt (cited in Mahoney & Goertz 2006) observes that the dynamics of the debate between quantitative and qualitative scholars on the validity of their methods are best understood by comparing it to one about religion, with deep cleavages between the two. Mahoney and Goertz (2006) provide an excellent discussion on how the two research traditions are to be understood as alternative cultures with proprietary values, beliefs, norms and language that may lead to severe "cross-cultural" communication problems when "forced" to work with each other. Thinking of different research traditions in terms of ethnocentric, coexisting and potentially conflicting cultures helps for explaining and mastering the challenges of collaborative research projects. One can draw on the large body of literature on culture in other academic disciplines, e.g. organizational behaviour and cultural studies. Clearly, parallels exist between methodological, organizational and ethnological culture. Considering the effective cultural barriers to collaboration even within science, it is not surprising that the barriers towards collaboration between science and NGOs or CSOs are even higher.

The Collaborative Scenario Definition Process

The collaborative scenario definition process proposed in the following[61] is a pragmatic interdisciplinary approach that aims at producing quantitative engineering/economics model scenarios in collaboration with civil society stakeholders. It is organized in four distinct phases. Phase 1 is concerned with establishing a fully functional project team and Phase 2 with establishing the technological framework conditions for the scenarios. The political framework conditions are elaborated with civil society stakeholders during Phase 3, resulting in scenarios that differ with respect to their degree of social acceptance. Phase 4 synthesizes.

[61] It is based on the experience from ENCI LowCarb, but presented on a meta level. It is applicable to projects involving the definition of scenarios with both technological and political framework conditions.

Core Project Partners

To accommodate the interdisciplinary requirements of the objective to include social dimensions in quantitative mitigation scenarios, core project partners come from both the scientific and the civil society communities. From the latter, NGOs constitute good candidates, as they form a continuously working formal entity, which cannot necessarily be generalized to all CSOs. Additionally, one can expect that NGOs are well embedded within the CSO landscape and act as facilitators between scientists and other CSOs. From the scientific communities, it is on the one hand necessary to have project partners from one or more research institutions that operate an engineering/economic type of quantitative model (here an energy system model), termed quantitative modelers, hereafter. On the other hand it is necessary to have project partners from the social sciences or humanities that are proficient in both quantitative and qualitative research methods of their discipline, termed social scientists hereafter[62]. Due to the distinct professional cultures of the project partners, it is decisive to stimulate their awareness for cultural issues in general and cultural differences in particular. A trivial, but effective means to achieve this is to define a core project team with each a research institution and NGO from at least two countries that do not share the same language. There are several practical advantages of combining the three different *professional cultures* with two or more different *national cultures*. Project partners communicate in a non-mother language, which fosters the awareness for unfamiliar terms and alleviates barriers to clarification requests during conversations. Furthermore, as the problem of climate change mitigation presents itself and is addressed very differently in individual countries, the transnational perspective helps to reframe and to challenge the purely domestic point of view.

Phase 1: Intra-Group Development

Albeit the intra-group development of project teams is a fairly standard procedure, a conscious group-formation process is of particular importance for collaboration across project partners from different communities. A suitable organizational structure is proposed in Figure 1. It resembles a matrix structure and enables vigorous communication flows between all

[62] In the following, it is assumed that both modelers and social scientists are from one research institution and the representative terms research institution, quantitative modeler, social scientist and NGO will be used in singular for simplicity; more than one project partner may be included from each community.

project partners; the colour codes visualize the different communities and countries. Tuckman (1965) observed that groups generally develop by passing through four distinct stages: forming, storming, norming and performing. Given project partners from different communities, with their respective cultural backgrounds, the first three stages need special attention for being successful in the fourth.

The forming stage of group development is characterized by uncertainty: project partners from the different communities are "testing the waters" and get acquainted to each other by exchanging ideas, expectations and world views; one gathers information and impressions of each other, but avoids open controversies or conflicts (Tuckman 1965). It is very likely that during this stage, many of the others' positions are not immediately obvious and even beyond clear assessment to the individual project partner. During the storming phase of group development, which is characterized by intra-group conflict and requires tolerance and patience, project partners express opinions and views more openly, including criticism (Tuckman 1965). One can expect that substantial cultural distance (Triandis 1994) exists between each the social scientist, the quantitative modeler and the NGO member. To overcome these, and enable the group to develop interdisciplinary approaches with regard to the specific research question of the project, conscious intercultural communication is advantageous. McDaniel, Samovar and Porter (2009, p. 13) argue that five aspects of culture are especially relevant to intercultural communication: perception, cognitive thinking patterns, verbal behaviours, nonverbal behaviours and the influence of context.

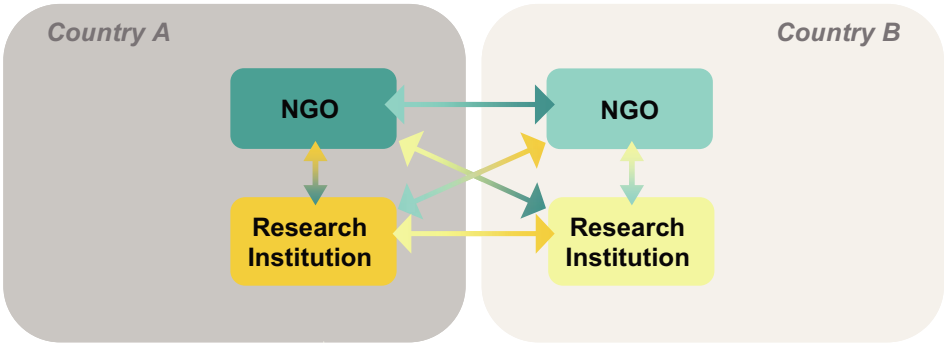

Figure 1. Organizational structure during Phase 1 of the collaborative scenario definition process.

A promising format to foster viable cross-cultural communication is to employ formal "wish-lists". The quantitative modeler receives model features that the others would like to see in the model and what kind of results they expect. The social scientist receives ideas on how social

acceptance is defined and will be explored, interpreted and measured. The NGO member receives considerations on what kind of stakeholders to consult. Such a process allows project partners to get a good understanding on how the others *perceive* their discipline. In a meeting, they present what they originally planned to contribute in the project and relates it to the "wish-list" items. Such an exercise will reveal their *cognitive thinking patterns*. After each presentation, sometime is reserved for clarifying terms, so project partners have a chance to realize potential *verbal* and *nonverbal* barriers to communication. Finally, in thematic sessions, the history and status quo of the domestic energy system can be presented, so one learns facts and *context* of the other country's challenges. During the "wish-list" process, the project partners have a chance to develop a common language and gain realistic expectations of the abilities of the quantitative model, the concept of social acceptance and the stakeholder landscape. In repetitive exchange, project partners develop a joint idea of the research methods they will employ. Finally, they pass the norming stage of group development, characterized by cohesiveness and in-group feeling, on to the performing stage, during which group energy is channelled into the task (Tuckman 1965).

Phase 2: Technological Framework Conditions

Phase 2 of the scenario definition process is concerned with model development and the technological framework conditions of the scenarios by involving external experts. The task is to refine the national quantitative models and bring them to a stage, in which they are applicable to stakeholder consultations, fulfilling as many "wish-list" items as feasible, driven by the overarching question of "What is technically possible in the future?". Thus, the social science issues regarding social acceptability do not yet enter the stage, they will be integrated in the next phase. Figure 2 proposes an organizational structure during Phase 2; with the core structure prevailing, but now the national sub-teams, indicated in green, have formed a tighter entity. This ideally results from the intense communication flows during Phase 1. The yellow shading of the consulted experts symbolizes the notion that they will most likely be closer to the researchers in terms of "professional culture" than to NGO members.

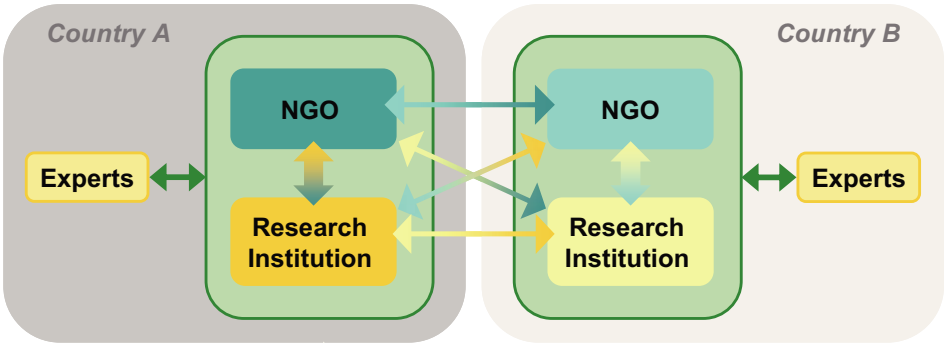

Figure 2. Organizational structure during Phase 2 of the collaborative scenario definition process.

Expert workshops are organized in each country, for the national sub-teams to engage in focus group discussions with experts for obtaining state-of the art knowledge on technical details. Thereby, the experts can assess the validity of the quantitative model and have a control function on the scientific quality. In the end of Phase 2, a finalized version of the energy system model exists, along with a detailed documentation that is also understandable to the non-technical reader. It is necessary to provide such a document during the stakeholder consultations in order to create transparency and alleviate the frequent black-box accusation when it comes to quantitative scenario building. Central to the model description are detailed translation rules, from "model parameters" to "real-world implications" and vice versa, that serve as a basis for taking into account political framework conditions explicitly.

Phase 3: Political Framework Conditions and Corresponding Scenarios

A central issue in Phase 3 of the collaborative scenario definition process is to elaborate different and potentially controversial political framework conditions with relevant CSO stakeholders. The political framework conditions relate to the quantitative model by applying the aforementioned translation rules from model parameters to "real-world implications". Coherent sets of political framework conditions form one scenario, differing with respect to the articulated level of social (un-)acceptability of mitigation options. The integrated scenarios are again evaluated by the CSO stakeholders. Figure 3 proposes an organizational structure for Phase 3. The blue shading of the CSO Stakeholders indicate that they are culturally close to the NGO project members, these indeed serve as facilitators in a two-step interaction in workshop format.

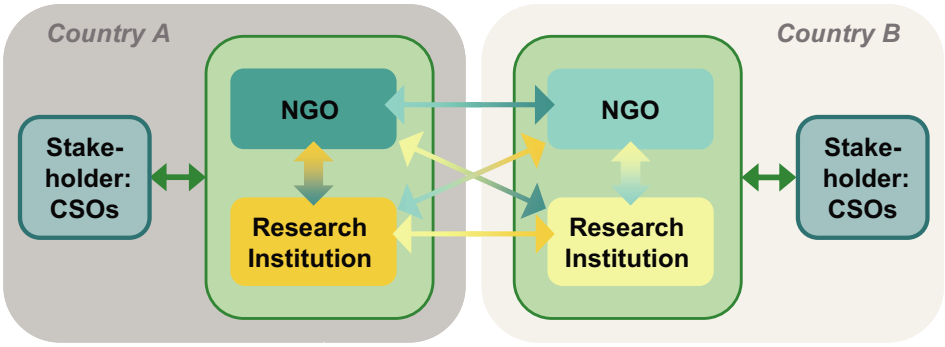

Figure 3. Organizational structure during Phase 3 of the collaborative scenario definition process.

Before inviting CSO stakeholders, the sub-national project teams identify sectors of the domestic energy system that are of particular interest or controversy regarding social acceptance. Together with a professional and neutral moderator, the national sub-teams develop concrete workshop agendas. The social scientist selects suitable methods for capturing stakeholder's assessments during the workshops. A practical format is a questionnaire with Likert scales (Likert 1932), measuring the level of agreement or disagreement of the respondent towards specific statements. The specific statements are the translated "real-world implications" and postulate particular and tangible developments[63]. Per item, two Likert scales are employed: Stakeholders are once asked to indicate whether they find the proposed development *realistic* and once whether they would *welcome* it from the point of view of their organization. Stakeholders are unlikely to express a uniform opinion, so several different sectoral "scenario building-bricks" in terms of political framework conditions will emerge from the workshops. The national sub-teams combine them into coherent scenarios for the fully integrated energy system, which serve as an input to the quantitative model. During the second sectoral stakeholder workshops, ideally attended by the same CSO representatives, the developed scenarios are presented, discussed, and evaluated. The feedback loop ensures that the social acceptance considerations are actually realized and gives the CSO representatives a chance to indicate their assessment of social (un-)acceptance of the integrated scenarios. At this stage, one possible outcome of the scenario definition process may be that the CSO representatives judge

[63] An example from the transport sector workshop of the ENCI LowCarb project is "Cycling and Walking will contribute substantially to the Modal Split. Please indicate your perception whether this is *realistic* and, separately, *welcome*, from the point of view of your organization on a 7-point scale from Yes to No.".

one or more integrated scenarios socially unacceptable as a whole, even though individual building bricks can be in line with their preferences.

Phase 4: Synthesis

The last phase is concerned with the synthesis of results obtained throughout the collaborative process, formalizing the outcomes of the stakeholder consultations as well as an evaluation of the final scenarios in terms of social acceptance. Ideally, a workshop communicates the scenarios to policy makers, stakeholders, and the wider public. Possibly valuable extensions for the collaborative process are to elaborate the political feasibility of the scenarios' political framework conditions as well as the reasons for social (un-)acceptance of specific mitigation options in more detail. Here, one could extend the socio-political point of view adopted during the collaborative scenario definition process, and analyse market and community acceptance.

The ENCI LowCarb Experience

The ENCI LowCarb project is financed in the 7th Framework of the EU Commission and constitutes a rather novel format involving both research institutes and NGOs. The core project partners are the Potsdam Institute for Climate Impact Research (PIK), Germanwatch, the Centre International de Recherche sur l'Environnement et le Développement (CIRED), and Reseau Action Climat France; the project phases, identified ex post, are summarized in Table 1.

	Phase 1	Phase 2	Phase 3	Phase 4
Objective	Intra-group development of the project team	Model building "What is technologically possible?"	Stakeholder workshops "What is socially desired?"	Synthesis, communication of scenarios
Leadership	Fragmented	Research Institution for sub-team in each country	NGO for sub-team in each country	Joint responsibility
Events	Kick-off meeting, Planning workshop	Expert workshops, Planning workshop	Repetitive CSO stakeholder workshops	Synthesis workshop, Communication Workshop
Deliverables / Output	"Wish-Lists" and feedback	Workshop summaries, model with description	Workshop summaries, national scenarios	Country reports, Comparative report
Time Horizon	6 months	12 months	12 months	6 months

Table 1. Overview of the phases in the collaborative scenario definition process within the ENCI LowCarb project.

ENCI LowCarb had two main project objectives: developing a reproducible methodology for engaging civil society, and preparing the German and French integrated energy system scenarios. The following reports on specific experiences made during the project on a more abstract level, with the intention to deliver beneficial input for future projects that involve collaboration between science and civil society, additive to the blueprint outline in Section 3. The German and French domestic energy system scenarios are accessible on the project website[64] upon publication.

Attitudes and Politics

In the beginning of the project, the different professional cultures and different intrinsic objectives of NGO members and scientists became tangible. NGOs are generally interested in developing scientific (counter-) expertise that can be used for proper lobbying activities, corresponding to their fundamental values. Especially, if the NGO is a network composed by several NGOs (like RAC-France), with individual future energy visions, there can be a strong internal pressure for obtaining politically relevant outcomes. Scientists have an interest in producing coherent, technically sound and objective research and tend to care less about the politics. These potentially

[64] http://www.lowcarbon-societies.eu

conflicting attitudes were made explicit early in the project. In later stages, many conflicts could be avoided due to project partners pointing out that the argument or problem at hand actually had to do with our different attitudes and perceptions, resulting in more productive discussions. Raising awareness for such issues proved to be crucial, especially during the definition of the integrated scenarios, as these were based on the stakeholders' assessments of *political* framework conditions.

Joint Understanding of Quantitative Models

Large and complex quantitative models are a very powerful tool for pursuing integrated system analyses; however, the models and their output are often meaningful only to the expert or insider. Outsiders are not enabled to judge the quality and validity of model results, and either have to believe the modelers, or not. During the ENCI LowCarb project, it was very important for the NGO members to learn more about quantitative models in general, and the models of the project partners in particular, so that modeling results can be put into perspective. It was a rather time-intensive process for the quantitative modelers to explain the models and was perceived as a real cross-cultural communication effort. During this process, it was very enlightening for the modelers to learn about the requirements from an NGO perspective, which sometimes differs substantially from academic peer group discussions.

For the NGOs, it was important to distinguish between means and measures in the energy system models: technical solutions, e.g. offshore wind turbines, and political measures to foster them, e.g. feed-in-tariffs. Whereas energy system models contain a whole range of technical solutions, it is not possible to integrate the full impact of political measures. NGOs are interested in a mixture of both, so it is helpful to differentiate and focus on what is feasible in the model during the project. The joint effort of clarifying the capabilities of the energy system models turned out to be a crucial success factor for the ENCI LowCarb project. The "wish-lists" introduced earlier were invented during the explanation process and turned out to be an extremely useful tool. The modeling teams were forced to think about the "real-world implications" of the aggregate model results and develop concrete translation rules on how parameters and variables may be expressed in tangible meaning. During the preparation and post processing of the stakeholder workshops these translation rules served as a helpful structuring element for the quantitative modelers.

From the perspective of the quantitative modelers, the expert meetings in Phase 2 were very helpful and stimulating. The modeling teams learned a lot

and sometimes revised the models according to the experts' opinions. Expert meetings are much more interactive than research conferences, where models are compared with other models, but not scrutinized in detail. For the NGOs, it was important to point out the sometimes double faced nature of experts, who are in fact also stakeholders, e.g. technical subjects like the necessary length of new transmission lines are a politically critical subject and even experts are not able to exclude this dimension from their opinions. For the NGOs, it was destabilizing sometimes that the modelers continuously improved their models, until the final scenarios were calculated. From the point of view of the researcher, this was natural to do, but it resulted in a situation in which the NGOs and became rather impatient as they wanted to see the model finished and ready to use. This should be anticipated and accompanied by setting and enforcing deadlines, sounding trivial, but proved to be a major source of conflict and dissatisfaction within the project team.

Stakeholder Workshops and Scenario Definition

The stakeholder workshops were the focal point toward which all efforts in the ENCI LowCarb projects were directed to. However, it was absolutely necessary to go through the first two phases of intra-group and model development for reaching a stage in which the project team was enabled to understand the stakeholders' requirements and translate them into coherent quantitative model scenarios. The preparation of the first stakeholder workshop was very demanding, as the agenda set here would determine the success of the collaborative procedure. The translation rules, from "the model" to "the real-world" and vice versa, had to be thematically summarized to determine those energy sectors (e.g. transport, electricity, heat) for which a feedback process was technically possible. For developing the agendas of the first sectoral CSO stakeholder workshops, the project team had to strike a balance between anticipating the areas in which social acceptance is problematic, and being prescriptive in the selection of topics. Furthermore, it was challenging to decide on how the stakeholder assessments would be collected, formalized, and grouped for constructing the integrated scenarios.

The stakeholder workshops on different energy sectors were stimulating and successful events. The instructions on the "scenario building bricks" in terms of political framework conditions were very valuable to the modelers. The workshops helped the project partners to understand which political scenario assumptions are socially more or less accepted, and specifically *why*. Due to the sector specific stakeholder workshops, particular attention

had to be paid to assure inter-sectoral coherence without neglecting the statements of the stakeholders for defining the final scenarios. A basic problem is that regarding energy system futures, there are many problematic technologies or developments in terms of social acceptance. However, it is not possible to define one scenario for each issue. This implies that the different options have to be combined into "worlds" that are structurally different, but still coherently reflect the stakeholder's assessments. Without the lengthy preparation of the translation rules from model to reality the project would have failed at this point. The synthesis phase can under certain circumstances be disappointing for the NGO partners. The final outcomes can be opposing to the principles of the NGO, which then hinders their communication on project results or even challenges the overall NGO strategy.

Limitations and Comparison

Limitations to the presented conceptual approach relate mainly to the reduction of complexity during the collaborative scenario definition process. One practical limit of the project's intention to develop socially acceptable scenarios is the necessity to find a compromise concerning the representation of stakeholder opinions. The national sub-teams select and invite stakeholders, thereby consciously limiting the wide range of opinions to a manageable number. It is an important task for the social scientist to ensure the representativeness of stakeholders. Furthermore, stakeholders that are invited to express their assessment and opinions during the workshop are situated in an artificial situation with rules established by the project partners, which may bias the discussion.

The focus of the ENCI LowCarb project was on socio-political acceptance; a representation of market and community acceptance were beyond the scope. One could, however, extend this in future projects and include more case-studies or field research for the social scientists to investigate and elaborate on these issues. It would also be interesting to include more than one model of each country, to overcome the risk of model bias. Another aspiration could be to include also industry and policy makers in the collaborative procedure, or, in a supplementary phase, one that would try to take into account the political feasibility of the measures generated by the previous process. Generally speaking, one should be careful about including too many core project partners, as this may be detrimental to Phase 1 of the process.

For putting these limitations into context, it is helpful to consider the methods and setup of other scenario processes that involved civil society

and/or stakeholder assessments and how they compare to ENCI LowCarb. However, there is to our knowledge no comparable project that was as transparent about the civil society stakeholders' roles. For example, Friends of the Earth Europe (FOEE) and the Stockholm Environment Institute (SEI) formally describe themselves as partners in a project aiming at developing an ambitious European mitigation scenario. The roles between FOEE and the SEI, however, were close to a traditional client agent relationship. FOEE fixed in advance technical assumptions on the availability of certain technologies in line with their internal strategy and SEI delivered the technical modeling knowledge. Nevertheless, several national FOEE associations were included in the initiative and a continuous exchange was established. It is interesting that the project partners decided to publish one publication each, supporting different communication strategies: FOEE (2009) and Heaps et al. (2009).

Another example is the European Climate Foundation (ECF) "Roadmap 2050" (ECF 2010), which outlines technically feasible pathways to achieve an 80% emission reduction target in 2050. Representatives of the EU institutions have been consulted periodically throughout the course of the project and a wide range of stakeholders (companies, consultancy firms, research centers and NGOs) have counselled ECF in the preparation of this report. Their names are mentioned, but not the method of how opinions were weighted, neither the rhythm of meetings. The hierarchy varied between project partners (a group of consultancies and research centers), core working group participants (European utilities, transmission system operators, clean tech manufacturers and CSOs) and further outreach (40 more companies, NGOs and research institutes). ECF tried to follow the recommendations in the scenarios, but claims to be solely responsible for the choices.

Then, the "Roadmap 2050" for a low carbon economy published in March 2011 by the European Commission (EC) (European Commission 2011a) comes with an impact assessment (European Commission 2011b) of three DGs, evaluating a set of possible future decarbonisation scenarios. The EC consulted individuals and stakeholders on their vision and opinion regarding an EU low carbon economy by 2050 through an online questionnaire "Roadmap for a low carbon economy by 2050"; 281 responses have been submitted. In its impact assessment, the EC declares that the wide range of views on how the EU can decarbonize its economy have been taken into account. However, the robustness of such an online questionnaire may be questioned. The core difference between these scenario processes and the ENCI LowCarb project is that here, domestic mitigation scenarios are one

outcome, embedded in a project foster cooperation between science and CSOs.

Conclusion

Quantitative low carbon scenarios, developed in response to the problem of climate change, clearly benefit from an introduction of sociological dimensions, in particular social acceptance. Addressing the social acceptance of mitigation options can by definition not be a one-way process from science to the public. In this paper, we propose a project design intending to foster collaboration between science and civil society for that purpose. One distinct feature is a conscious emphasis on intra-group development, accounting for the issue that collaboration partners come from significantly different and potentially conflicting professional cultures; a situation that may give rise to severe communication barriers. NGOs and researchers can learn substantially of each other and create a mutual understanding of appropriate methods and perspectives. This enables the development of interdisciplinary research methodologies, intertwining both qualitative and quantitative tools of the different scientific disciplines.

In order to structure a collaborative scenario definition process, it is helpful to differentiate between technological and political framework conditions that serve as an input to the quantitative models. Experts are invited to define the technological framework conditions. The configurations of political framework decisions are guided and evaluated by relevant CSO stakeholders. A necessary prerequisite is that aggregate model input and output data are translated into tangible meaning. However, the methodology and organization of such a process is to date not well studied and should be developed formally for empowering more collaborative scenario definition processes in the future. In the end, this process can lead to the conceptualization of innovative low carbon scenarios that take into account social dimensions, in particular the social (un-)acceptance of mitigation options.

Meaningful energy system scenarios and policy roadmaps can only be developed if such organizational setups become more mainstream. Civil society has to be involved in solutions of climate change mitigation; purely academic solutions will not be successful. Climate change is not an isolated environmental problem like the ozone-hole, where there is one clear cause and one clear solution, but it is a problem whose solution will affect the entire economy and therefore the whole global society.

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Chapter 3

REMIND-D: A Hybrid Energy-Economy Model of Germany *

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NOTA DI LAVORO

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REMIND-D: A Hybrid Energy-Economy Model of Germany

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Summary

This paper presents a detailed documentation of the hybrid energy-economy model REMIND-D. REMIND-D is a Ramsey-type growth model for Germany that integrates a detailed bottom-up energy system module, coupled by a hard link. The model provides a quantitative framework for analyzing long-term domestic CO2 emission reduction scenarios. Due to its hybrid nature, REMIND-D facilitates an integrated analysis of the interplay between technological mitigation options in the different sectors of the energy system as well as overall macroeconomic dynamics. REMIND-D is an intertemporal optimization model, featuring optimal annual mitigation effort and technology deployment as a model output. In order to provide transparency on model assumptions, this paper gives an overview of the model structure, the input data used to calibrate REMIND-D to the Federal Republic of Germany, as well as the techno-economic parameters of the technologies considered in the energy system module.

Keywords: Hybrid Model, Germany, Energy System, Domestic Mitigation

JEL Classification: O41, O52, Q43

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REMIND-D: A Hybrid Energy-Economy Model of Germany

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Contents

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1 Introduction

Global climate models indicate that a mitigation effort of ≈50% global greenhouse gas (GHG) emissions in 2050 relative to 1990 yields a likely chance of keeping global warming below 2°C (Meinshausen et al. 2009). Germany contributed nearly 5% of global GHG emissions in 2007 (UNFCCC 2009), of which carbon dioxide (CO_2) constituted the largest share with 87%. Figure 1 illustrates how German domestic CO_2 emissions can be attributed to the sectors land use, industrial processes[1] and the energy sector in the year 2007. The energy sector has been causing a stable share of ±80% of total German CO_2 emissions every year since 1990 (UBA 2010). Hence, decarbonizing the energy system is central to achieving cuts in German GHG emissions. A long-term CO_2 emission reduction target of 80-95% in 2050 relative to 1990 has been announced by the German Government (Bundesregierung 2010). Achieving such an ambitious mitigation target will require a structural transformation of the German energy system.

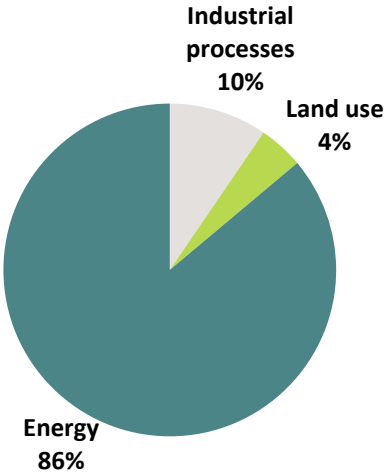


Figure 1: Shares in German CO_2 emissions in 2007 by source. Own illustration with data from UBA (2010).

Energy system transformations are large-scale processes subject to inertia, due to capital intensive infrastructure and conversion technologies as these usually have technical lifetimes of several decades. Long-term planning is necessary for enabling low carbon technologies in future energy system portfolios. An important tool for exploring the future and dealing with complexity and uncertainty are scenarios, especially when formalized by means of an energy-economy model. Ideally, such a model included all technological and socio-economic processes and systemic feedback loops that are observed in reality. Unfortunately, computational costs, data scarcity and data unobservability as well as a lack of conceptual frameworks and economic theories set limiting boundaries.

[1] These are mainly emissions from mineral products, chemical industry and metal production.

Existing energy-economy models represent selected aspects of the energy-economy nexus and their results inherently reflect the adopted methodology of the model. Classification typologies vary greatly in the literature, e.g. according to (numerical) methodology (Nakata 2004) or descriptive versus normative argumentation structures (McDowall and Eames 2006). A widely agreed differentiation is to group energy-economy models into "top-down" versus "bottom-up" approaches. Top-down models follow an economic approach and endogenize behavioral relationships by calibrating on market data, assuming no discontinuities in historical trends. Bottom-up approaches, on the other hand, follow an engineering approach and contain detailed descriptions of technologies and technical potentials, assuming market adoption of the most efficient technologies (Hourcade and Robinson 1996).

In early global mitigation analyses, bottom-up models systematically indicated larger GHG reduction potentials than top-down models. Hence, Grubb et al. (1993) labeled top-down models as pessimistic and bottom-up models as optimistic. They attributed the difference to the existence of negative cost potentials, so called 'no regrets' options, in bottom-up approaches. These refer to emission reductions caused by the adoption of best available techniques whose costs are lower than the technologies currently in use, i.e. an efficiency gap. The size and meaning of this efficiency gap is subject to controversy in the debate between modeling approaches. It arises particularly due to the different approaches of modeling technological change.

Engineering-oriented bottom-up studies suggest that market forces do not operate perfectly and the policy implication is to remove barriers to adoption of the best available technique (Hourcade and Robinson 1996). Opposingly, economists argue that these postulated market failures are only apparent and can be explained in terms of two other factors: complexity and heterogeneity of consumer preferences and hidden costs, e.g. information costs or perceived risks associated with capital costs. In calibrated top-down models, this complex set of behavioral factors is captured in price and income elasticities. In a more recent analysis, Vuuren et al. (2009) find no systematic difference in the reduction potential reported by state-of-the-art top-down and bottom-up models at the global scale. However, the results at the sectorial level show considerable differences in terms of technical versus economical reduction potential. It is concluded that the two approaches are complementary in the sense that they add different types of information. While the bottom-up approach is stronger in terms of technology resolution, top-town models enable a sectorially integrated analysis by incorporating economic feedback loops.

For analyzing domestic CO_2 reduction potentials in Germany, bottom-up models dominate the literature, e.g. PERSEUS (Fichtner et al. 2001), TIMES-D (Blesl et al. 2007), IKARUS (Martinsen et al. 2006) and the Prognos model (Kirchner et al. 2009). They are demand driven and technology oriented. The models solve a partial equilibrium problem by minimizing an energy system cost metric, consisting of total fuel, maintenance and investment costs. Recently, some effort has been made to establish soft links between different models to consider feedback loops, e.g. Schlesinger et al. (2010) couple the bottom-up Prognos model with the top-down econometric PHANTA RHEI (Meyer et al.

2007) model and a detailed dispatch model of the German electricity sector. Soft-linking allows for some feedback, but the different models continue to individually optimize their objective functions. While the German GHG reduction potential has been extensively analyzed in terms of technical potential, the economic potential has received very little attention, due to a lack of models suitable for this type of analysis.

In order to fill this gap, a hybrid energy-economy model for Germany has been developed at the Potsdam Institute for Climate Impact Research: REMIND-D (Refined Model of Investment and Technological Development - Deutschland). Hard-link hybrid models integrate a detailed bottom-up energy sector into a top-down representation of the macro economy. In this manner, capital and resources for energy generation are allocated optimally with respect to the whole economy (Bauer et al. 2008). Hybrid models have been developed to overcome the drawbacks of pure top-down or bottom-up models and are well established in global integrated assessment exercises, e.g. WITCH (Bosetti et al. 2006) and REMIND-R (Leimbach et al. 2010). REMIND-D builds on the structural equations of the state-of-the art global integrated assessment model REMIND-R. All structural equations are reported in detail in Bauer et al. (2011)[2]. Hence, this document refrains from reproducing all equations in REMIND-D. Instead, it intends to provide an extensive documentation of the input data used to calibrate REMIND-D to the Federal Republic of Germany.

2 The Model REMIND-D

The basic purpose of REMIND-D is to provide a quantitative framework for analyzing long-term domestic mitigation scenarios for Germany, enabling a focus on the economic reduction potential. The technological reduction potential is considered explicitly by a detailed bottom-up energy system module. REMIND-D facilitates an integrated analysis of the long-term interplay between technological mitigation options in the different sectors as well as macroeconomic dynamics.

A stylized overview of REMIND-D's structure is illustrated in Figure 2. The top-down macroeconomic module resembles a Ramsey-type neoclassical optimal growth model (Cass 1965; Koopmans 1965; Ramsey 1928). Output is produced by aggregating the production factors capital, labor and energy via nested Constant Elasticity of Substitution (CES) functions. The production factor energy is subdivided so as to match the aggregated final energy demand of the industry and residential & commercial sector as well as the energy service demand of the transport sector. These quantities are provided by a bottom-up energy system module that considers the techno-economic characteristics of conventional and prospective energy conversion technologies explicitly. CO_2 emissions accounting is pursued via emission factors on fossil fuel consumption. For solving REMIND-D numerically, it is formulated as an intertemporal social planner problem

[2] Accessible online via `http://www.pik-potsdam.de/research/sustainable-solutions/models/remind/remind-equations.pdf`

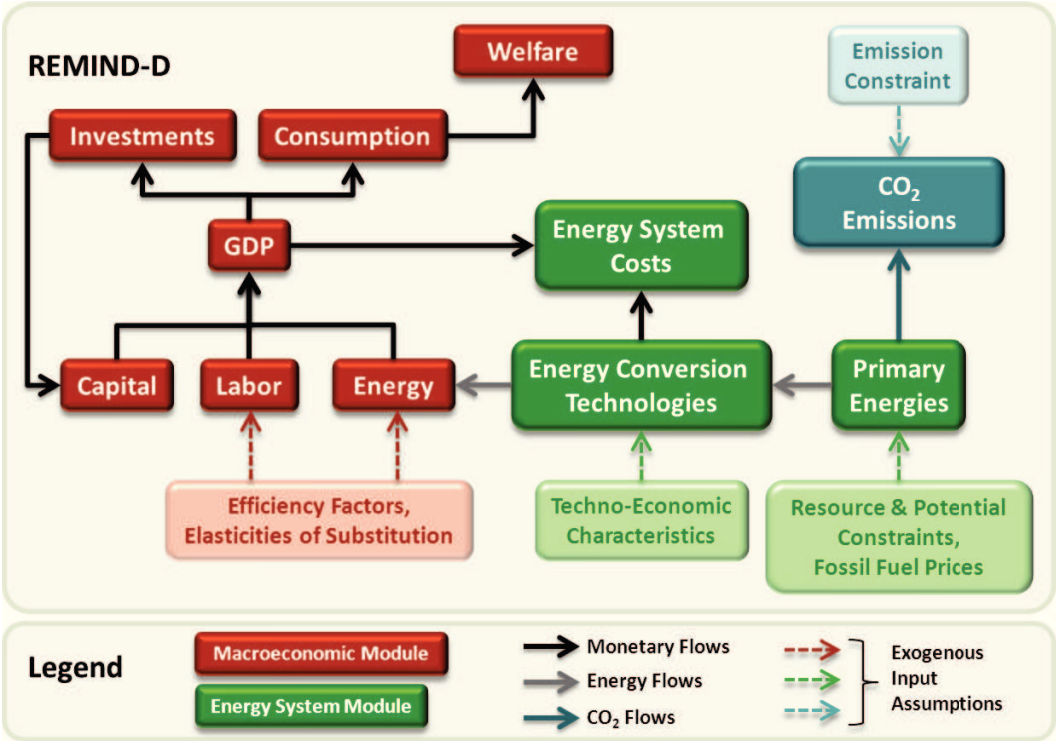


Figure 2: Stylized overview of REMIND-D's structure.

with perfect foresight. It maximizes an intertemporal social welfare function by determining optimal time paths of control variables subject to exogenous constraints. The control variables are investments into the macroeconomic capital stock, final energy and energy service demand, investments into energy conversion technologies and operation & maintenance as well as fuel costs.

The optimization space of the model is numerically constrained by technical resource and potential constraints of domestic primary energy supply (lignite, biomass, wind, solar and geothermal) and the energy conversion capacities' efficiency grades. Economically, it is constrained by fossil fuel prices, cost developments of low-carbon technologies as well as the exogenous efficiency factors and substitution elasticities in the production function. In the standard setting, mitigation policy is enforced in REMIND-D via a CO_2 budget that may be allocated intertemporally. Alternatively, specific carbon tax or emission trajectories can be imposed on the model. One particular set of constraints defines a scenario. The analysis of two scenarios that differ only with respect to the emission constraint allows for determining the differential effects of mitigation policy. In optimization models, the introduction of perturbation like a binding emission constraint or pricing carbon emissions will automatically lead to a non-optimal solution. Consequentially, mitigation costs will always be negative. Due to a lack of conceptual frameworks,

positive co-benefits of mitigation are not included in the social welfare function.

Underlying assumptions of the optimization approach with a Ramsey-type growth model are discussed extensively in e.g. Maußner and Klump. (1996). The most important ones include that the economy is closed and no government exists that demands or supplies goods. The economy is comprised of two sectors: households and firms. Firms produce output by using the three production factors capital, labor and energy. Households are equal in initial endowments and preferences, which are ordinal. The assumption of representative households allows for an intragenerational aggregation of individual utilities. The ordinal preference orderings justifies the intertemporal aggregation of utilities, which is achieved by summing discounted utilities. Even though these assumptions are disputable, they are necessary simplifications for the analytical framework and relaxations incurred prohibitively high numerical costs due to the integration of the complex bottom-up energy system module.

An implication of these underlying assumptions is that a Ramsey-type growth model is only suitable for analyzing certain questions. For example, REMIND-D is ill-suited to analyze the distributional effects of climate policy. Originally, (Ramsey 1928) asked the question of "How much shold a nation save?" and operationalized it by asking "How much should a nation consume?" instead. By integrating energy as an additional production factor as well as a detailed representation of its supply chain and the carbon externality into the modeling framework, REMIND-D shifts the focus of analysis. The standard mode of analysis reads as: "Given the German energy system is subject to a specific carbon budget and set of scenario definition constraints, what is the most welfare-optimal mitigation strategy?".

The following summarizes fundamental information on REMIND-D. Calibration input for the macroeconomic and energy system modules is presented in Section 3 and Section 4. The calibration base year is 2007. Section 5 reports on the CO_2 emission accounting procedure. Finally, Section 6 provides a brief validation of model results.

2.1 Fundamentals

Programming Language and Solver The model is written in GAMS and uses the non-linear solver CONOPT.

Time The time horizon for the optimization is 2005-2100, with a discrete time step resolution of 5 years. The first time step, "2005", covers the period 2005-2009. The calibration of the model is performed for the year 2007, the median year in the range. Subject to analysis are the consecutive time steps from 2005 to 2050. The reason for excluding the later years from the analysis is the occurrence of undesirable "burn-out" effects towards the end of the simulation period. It is common practice in optimization models to cut off the period of analysis ahead of the end of the time horizon.

Fluctuating Renewables Variable renewable electricity generation fluctuates on very short time scales. Since the time resolution in REMIND-D is in 5 year time-steps, these effects cannot be modeled explicitly. However, neglecting the system requirements that arise from high penetrations of fluctuating renewables significantly understates the integration costs of renewables. In REMIND-D, a residual load duration curve approach captures most of the challenges that arise from high shares of fluctuating renewables without increasing the temporal resolution of the model. Ueckerdt et al. (2011) elaborates of the concept and validates the approach with a detailed dispatch model of Germany.

Geographical Resolution As a system boundary for REMIND-D, the geographical borders of Germany guide the cut-off since the focus of the model is on *domestic* mitigation. Imported energy carriers come at exogenous prices and Germany is assumed to act as a price taker. Within the model, the geographical dimension is parameterized in an appropriate way for covering geographic first-order effects, e.g. distribution technologies. REMIND-D is a single-region model.

Demand Sectors REMIND-D considers the aggregated demand sectors industry (IND), residential & commercial (RES&COM) and transport. Each sector demands different final energies, or in the case of the transport sector energy services. Elasticities of substitution determine the endogenous development over time.

Equilibrium The concept of equilibrium means that a system is in a state that will not change unless external influences change one or more variables. A market that is in equilibrium is in a state such that supply and demand match at the equilibrium price. There are many ways to find the equilibrium solution for a system. REMIND-D chooses to do so by maximizing the intertemporal welfare. According to the 2nd theorem of welfare economics, such a solution coincides with the market solution under the assumption of Pareto-efficiency. REMIND-D finds a simultaneous equilibrium in capital and energy markets.

Perfect Foresight The assumption of perfect foresight is a theoretical assumption necessary in the model setup for finding a solution to the equilibrium problem. Perfect foresight essentially means that the long-term consequences of a particular decision in a particular year are entirely foreseeable for the solution process. The solution process for REMIND-D is iterative, meaning the solver calculates a particular solution pathway over the time horizon and reaches a particular value for the optimization objective and stores it. In the next iteration, some alternative decision is made in the solution pathway and the solver compares the new value for the optimization objective to the one previously obtained. If it is higher, the older pathway is dropped and the new pathway serves as a benchmark. Again, some decision is altered and the objective value compared. This process repeats until the change in the optimization objective is continuously below a certain threshold, which is a very small number. In this case, the solution process ends and an optimal solution is reported. The concept of perfect foresight in REMIND-D implies that

the results of the model represent optimal pathways and are not expert forecasts or simulations.

Myopic Behavior Fixing certain variables for a selected period of time on a pathway that does not coincide with the optimal solution is a means of introducing myopic behavior into the model. Upon comparing results from a complete perfect foresight model run with one that includes myopic behavior allows for distilling its effects.

Discounting The pure time preference rate in REMIND is rate is set to 1% in the standard setting. Endogenously, the interest rate adjusts to ±3%, depending on the scenario and time step. Thus, for the discounting of GDP losses, a discount rate of 3% is used in the standard setting.

Endogenous Learning REMIND-D draws on the concept of learning-by-doing (Arrow 1962) for modeling the cost functions of innovative low carbon technologies endogenously. The application of the concept to bottom-up energy system models was pioneered by Messner (1997) and Barreto (2001). For a critical discussion see Kahouli-Brahmi (2008) or Nordhaus (2008). The underlying idea is that, historically, the specific investment costs of technologies have been reduced significantly with increased installed capacity. Learning rates are a means to express how much the specific investment costs reduce upon a doubling of installed capacity. The innovative low-carbon technologies in REMIND-D are subject to non-linear, endogenous learning that is split into domestic and global components, implying the reasoning that for some components global capacities are the main drivers and for others national capacities.

Scenario The term scenario refers to one particular set of constraints of the optimization space, i.e. one set of exogenous assumptions.

Mitigation Enforcement In the standard setting, mitigation is enforced via a domestic CO_2 budget over the time horizon, inspired by Meinshausen et al. (2009) and WBGU (2009). Other possible implementations include prescribing a CO_2 tax or a specific annual emission trajectory.

Baseline Scenario In the Integrated Assessment community, often a baseline scenario is one that has unconstrained GHG emissions. For Germany, such a pure baseline is unlikely as emission reduction policies are already in place and commitments are high. The definition of a baseline scenario for REMIND-D consequently follows the idea that mitigation continues at a moderate level, i.e. reaches around 40% CO_2 domestic emission reduction in 2050 versus the 1990 level.

Policy Scenario In the context of REMIND-D a policy scenario is one that is subject to a stricter CO_2 emission reduction target than the baseline scenario.

Mitigation Costs Comparing the results of a baseline and policy scenario that differ only with respect to the emission constraint allows for determining the differential effects of mitigation policy. This implies a cost-effectiveness mode of analysis. Climate damages and positive co-benefits of mitigation are not considered in REMIND-D.

Mitigation costs are inherently negative and may be analyzed on all levels, e.g. from GDP losses to differences in electricity prices.

3 The Macroeconomic Module

The macroeconomic module of REMIND-D comprises the optimization objective, a social welfare function, and the production function. They are calibrated to represent the aggregate of German households and firms, respectively. While a hybrid economy-energy system model is theoretically intriguing, it is very challenging to calibrate it to a particular country. This is due to the fact that energy demand is represented endogenously by nested CES-functions, which require substitution elasticities, factor productivity growth rates and initial relative prices for calibration. The usual procedure for a Ramsey-type growth model is to operate under an input-validation paradigm and estimate them econometrically based on past data. However, for the most of the production factors in the case at hand, these data are unobservable. The time series which are potentially available only go back to 1991 for unified Germany. Such short time series yield insignificant econometric results. An alternative is to calibrate the model based on output-validation.

One means of providing output-validation is to rely on heuristics and calibrate the model behavior so it reproduces future developments that are judged as highly likely by expert consensus. Two heuristics serve for calibrating REMIND-D for Germany. (1) In a baseline scenario, with only moderate mitigation, historical trends in observable variables will continue smoothly. (2) In an ambitious mitigation policy scenario, energy demand will evolve in line with the predictions of detailed bottom-up energy system models. The calibration parameters in the macroeconomic module are adjusted through trial-and-error so as to fulfill these two heuristics as good as possible. The calibration was evaluated and improved in dedicated expert workshops within the ENCI LowCarb (Engaging Civil Society in Low Carbon Scenarios) [3] project.

3.1 Optimization Objective

The optimization objective of REMIND-D is an intertemporal social welfare function that depends on the intertemporal sum of logarithmic per capita consumption, i.e. utility U. For the underlying assumptions consult Maußner and Klump. (1996).

$$U = \sum_{t=t_0}^{T} \left(\Delta t \cdot e^{\xi(t-t_0)} L_t \cdot \ln\left(\frac{C_t}{L_t}\right)\right) \tag{1}$$

The variables L_t and C_t are population and consumption and the subscript t indicates time. We assume a pure rate of time preference ξ of 1%. The logarithmic functional

[3] ENCI LowCarb is financed by the 7th Framework Programme for Research of the European Commission. For further information please visit www.lowcarbon-societies.eu.

Table 1: Assumed development of the German population in Million inhabitants (Kirchner et al. 2009).

2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
82.41	81.89	81.10	79.80	79.19	78.58	77.28	75.98	74.07	72.17

relationship between per-capita consumption and utility results from assuming the intertemporal elasticity of substitution to equal one. Via the steady state conditions and the Keynes-Ramsey rule, the endogenous interest rate amounts to around 3%; the exact value ultimately depends on the endogenous economic growth rate in the respective time step. If desired, the pure rate of time preference in the model can be altered. Table 1 reports the population forecast that is assumed in REMIND-D. It is derived from (Kirchner et al. 2009), who base their forecast on the prognosis from the national statistics bureau (Statistisches Bundesamt 2006).

3.2 Production Function

The backbone of the macroeconomic module is the production function, which ultimately determines the macroeconomic output Y, i.e. the gross domestic product (GDP). The production function applied in REMIND-D is a nested "Constant Elasticity of Substitution" (CES) production function. On the highest level, the production factor inputs considered are capital, labor and energy, with the latter being determined by several sub-nested CES-functions that are constructed according to the substitutability in terms of providing similar useful energy or energy services.

Formally, the production function is defined as follows for each layer described by the mapping M_{CES}, assigning the respective output factor $V_t(\upsilon_{out})$ to the available input factors $V_t(\upsilon_{in})$.

$$V_t(\upsilon_{out}) = \phi(\upsilon_{out}) \cdot \left(\sum_{M_{CES}} (\theta_t(\upsilon_{in}) \cdot V_t(\upsilon_{in}))^{\rho(\upsilon_{out})} \right)^{\frac{1}{\rho(\upsilon_{out})}} \quad \forall t, \upsilon_{out} \tag{2}$$

$$M_{CES} = (\upsilon_{in} \times \upsilon_{out}) \in \mathfrak{M}_{CES}$$

The parameter $\phi(\upsilon_{out})$ is a scaling factor that represents total factor productivity and is set equal to one in REMIND-D. The parameter $\theta_t(\upsilon_{in})$ represents an efficiency factor that is determined endogenously for each production factor in the first time period based on its income share and the relative price of supplying one unit of the demanded production factor. The relative prices in the first time period are derived from the calibrated energy system. The growth rate of the efficiency factor is an exogenous input. The parameter

$\rho(v_{out})$ is determined by the elasticity of substitution σ defined for each CES-nest. The definition is according to Equation 3.

$$\sigma = \frac{1}{(1-\rho)} \tag{3}$$

For a graphical illustration of the production function mapping M_{CES} and elasticities of substitution σ see Figure 3. Note that all outputs (intermediate and GDP) represent monetary values. Table 2 reports the efficiency factors $\theta_t(v_{in})$ for each final energy demand.

The elasticities of substitution in the nested CES function have a techno-economic inter-

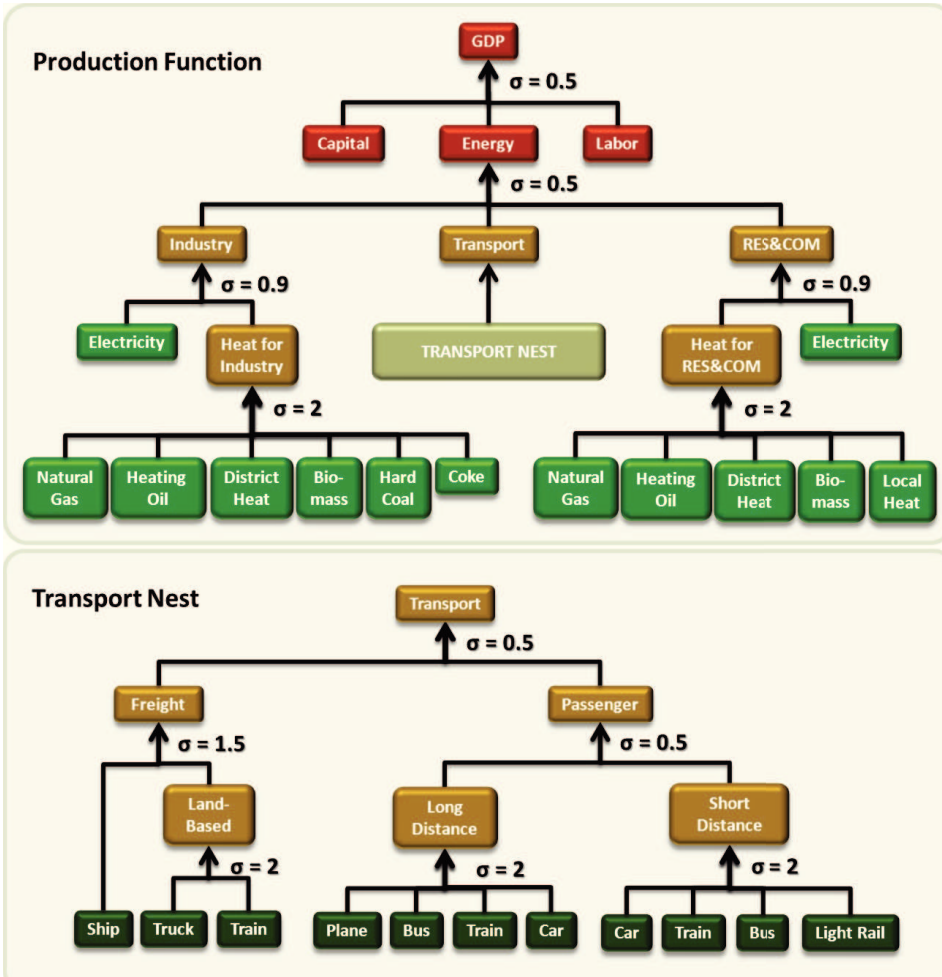


Figure 3: The nested CES-production function of REMIND-D with substitution elasticities σ. RES&COM = Residential & Commercial.

Table 2: Assumed growth rates of the efficiency factor $\theta_t(\upsilon_{in})$ in %.

%	Industry	RES&COM	Gt/Gp-km	Freight	PFD	PSD
Natural Gas	1.44	0.40	Ship	0.50		
Electricity	1.18	1.47	Truck	0.50		
District Heat	1.52	0.40	Train	0.50	1.50	1.50
Heating Oil	2.75	-9.00	Car		1.50	1.50
Biomass	1.18	0.60	Light Rail			1.20
Local Heat		0.60	Bus		1.50	1.20
Coke	2.65		Airplane		1.20	
Hard Coal	2.65					

pretation. For example, from an engineering point of view it is a simple task to substitute an oil furnace for a gas furnace in households. However, energy for industry and energy for transport are economic complements. In general, the substitutability increases with the level of detail in the branches. Depending on the substitution elasticity of the respective CES-nest, the effect of the efficiency growth rates is substantially different: If $\sigma < 1$, the production function demands relatively less from an input with higher $\theta_t(\upsilon_{in})$, and vice versa if $\sigma > 1$. This is also valid for aggregate intermediate factors. Assumptions about the growth rates of the efficiency factors $\theta_t(\upsilon_{in})$ are difficult to obtain from empirical data as these efficiency growth rates unify a variety of unobservable factors. The underlying idea is that over time more output may be produced from the same amount of input because the use of the final energy becomes ever more efficient. Essentially this argument rests on the idea of technological progress. However, the technological progress in the energy supply chain is represented explicitly in the energy system module. Separability of technological progress and demand reductions due to sufficiency is not measurable. Hence, the exogenous growth rates of the efficiency factors $\theta_t(\upsilon_{in})$ are chosen as to fulfill the two heuristics introduced above.

In the calibration year 2007, the GDP in Germany was 2428 billion € (Statistisches Bundesamt 2012) and the capital stock amounted to 10,206 billion € (Statistisches Bundesamt 2009). The production factor labor is assumed to be price-inelastic and population is used as a proxy. As a consequence of this simplifying practice, the labor force is assumed to develop proportionally to the total population. For this reason, REMIND-D is not suitable to analyze the labor market implications of mitigation.

3.3 Energy Demand

The energy demand in REMIND-D is modeled as an aggregate for each of the three end-use sectors industry, residential & commercial (RES&COM) and transport, as defined in the German energy balances (AGEnergiebilanzen 2010). In REMIND-D the sectors industry and the RES&COM demand final energy carriers; the specific appliances that convert these energy carriers to useful energy are beyond the scope of the model. This

Table 3: The left panel displays the final energy demand in Germany for 2007 in PJ, the data are from AG Energiebilanzen (2010). The right panel displays the energy service demand of the sectors domestic Freight and Passenger Transport in billion ton-km (Gt-km) and billion person-km (Gp-km), respectively. PLD stands for 'passenger long distance', PSD for 'passenger short distance'. Data are based on BMVBS (2008); Kirchner et al. (2009); UBA (2009).

PJ	Industry	RES&COM	Gt/Gp-km	Freight	PLD	PSD
Natural Gas	945	1316	Ship	65		
Electricity	850	985	Truck	476		
District Heat	151	290	Train	114	35	45
Heating Oil	136	863	Car		339	549
Biomass	64	189	Light Rail			17
Local Heat		21	Bus		17	37
Coke	169		Airplane		59	
Hard Coal	167					

is different for the transport sector – here energy services in terms of ton-km (t-km) or person-km (p-km) are demanded, since transport technologies are modeled explicitly in the energy system module. Table 3 reports the initial energy demands in the calibration year 2007. The Industry sector consists of the branches mining, stone & clay quarrying and manufacturing and is based on the classification by the Federal Statistical Office. The RES&COM sector is rather heterogeneous and includes private households, manufacturing firms with fewer than 20 employees not included in manufacturing industry, commercial properties and enterprise premises, agriculture, commercial enterprises and private and public service companies and organizations. In the transport sector, a general differentiation is made between freight transport and passenger transport. Passenger transport is further subdivided into modal split and long and short distance.

3.4 Hard Link

The cost side of the hard link between the energy system module and the macroeconomic module is ensured by the budget equation illustrated in Equation 4, posing that output Y_t has to cover the investments into the macroeconomic capital stock I_t and all costs incurred by the energy system E_t. Consumption C_t enters the social welfare function. The production factor part of the hard link operates via individually equating the final energy and energy service demands of the macroeconomic module with those generated by the bottom-up energy system module.

$$Y_t = C_t + I_t + E_t \qquad \forall t \tag{4}$$

4 The Energy System Module

The bottom-up energy system module (ESM) of REMIND-D is calibrated to represent the German energy supply chain. Figure 4 sketches the general structure. Technically, the different levels of primary, secondary and final energy / energy services are interconnected by a set of balance and transformation equations. This section presents the calibration input data, the equations are in Bauer et al. (2011).

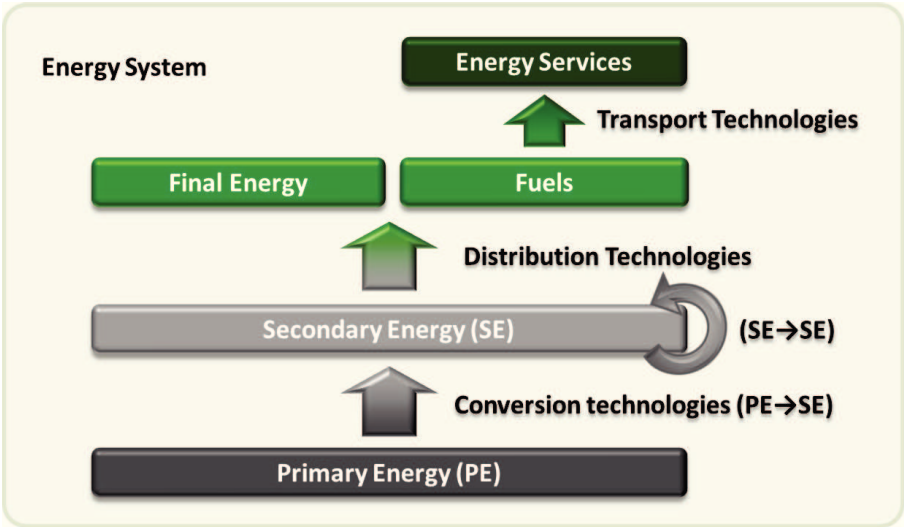


Figure 4: Schematic representation of the energy system module in REMIND-D.

Primary energy (PE) considered in REMIND-D are lignite, hard coal, crude oil, natural gas, uranium, wind power, solar irradiation, geothermal energy, hydro power and biomass. These constitute the plausible options for the German energy supply and are either imported or mined/used domestically. Section 4.1 elaborates on the potential, resource and price assumptions. PE is converted into SE by a multitude of energy conversion technologies. General characteristics of technologies in REMIND-D are introduced in Section 4.2. The detailed techno-economic parameterization is reported in Section 4.3, for both PE→SE conversion technologies (4.3.1) and SE→SE conversion technologies (4.3.2). SEs include electricity, hydrogen, district heat, coke, petrol, diesel, kerosene, heating oil, heavy fuel oil, biomass for industry and households, hard coal for industry, natural gas and local heat. To meet the final energy demand of the industry and RES&COM sector as well as fuel demand of the transport sector, the SEs are distributed with stylized technologies that proxy infrastructure requirements. These technologies are introduced in Section 4.4. Fuels are further converted into energy services by means of transport technologies, which are presented in Section 4.5.

4.1 Primary Energy

The ESM of REMIND-D considers renewable energy carriers, biomass and exhaustible fossil energy carriers. They characteristics differ in terms of associated CO_2 emissions and whether increased usage leads to an increase in fuel costs. Renewable energy is free of CO_2 emissions and free of fuel costs. Biomass is free of CO_2 emissions but increased usage leads to an increase in fuel costs. However, the use of renewable energies as well as biomass is limited to a specific technical potential. Exhaustible fossil energy carriers are CO_2 intensive and increased usage leads to an increase in fuel costs.

Renewable Energy Sources Renewable domestic primary energy sources include solar, wind onshore, wind offshore, deep geothermal, geothermal near-surface (for heat) and hydro. Table 4 gives an overview of the technical potentials estimated by different studies for Germany. Some differ substantially across the various studies. Reasons for the differences lie in differing assumptions on which the calculation of the technical potential rests. These are quite complex, including e.g. the size of the geographical region on which a primary energy carrier may be exploited and the distribution of wind speed or solar irradiation. In REMIND-D, each renewable potential is subdivided into different grades, representing the different quality classes of geographical sites with respect to average annual full load hours. Renewable energy technologies thus exhibit a gradual expansion with the best geographical sites exploited first, followed by those yielding less energy per area and year.

Table 4: Overview of technical potential estimates for renewable energy sources in TWh/a. The potentials assumed in REMIND-D are based further on BMU (2008) Scenario E-3, Nitsch et al. (2004) and Paschen et al. (2003).

TWh/a	BMU (2008)	UBA (2010)	SRU (2010)	REMIND-D
Solar-el.	105	248	112	105
Solar-th.	300	-	-	100
Wind-on.	68	180	90	90
Wind-off.	135	180	317	180
Geo-el.	150	50	223	64
Geo-th.	330	-	-	100
Hydro	25	24	28	28

Biomass Biomass differs from other renewable energy carriers in the sense that increased usage leads to an increase in fuel costs. This is represented by a biomass supply curve which is defined only up to a potential limit. As grown biomass is in competition with the food industry, the potential limit is up to political decisions on how much agricultural land may be used for energetic and how much may be used for food purposes.

Table 5 illustrates the assumed domestic higher-heating value potentials for Germany in 2005 and 2050, which are rather conservative. It is assumed that potentials for lignocellulose, sugar/starch and oily biomass linearly increase until 2050 and then stay constant. We assume that lignocellulose is only gained from scrap wood. The farmland used for the biomass potential may at most be quadrupled as compared to 2005. The potential for manure is already reached, as a major expansion of the livestock industry in Germany is not likely.

Table 5: Biomass potentials in REMIND-D for 2005/2050, from Nitsch et al. (2004) Variant "Naturschutz Plus" Scenario B. They are assumed to increase linearly between 2005 and 2050.

	BioLC (Lignocellulose)	BioSS (Sugar&Starch)	BioO (Oil)	BioM (Manure)
Potential[PJ/a]	450/700	40/250	60/200	150/150

Exhaustibles The fossil primary energy carriers crude oil, natural gas and hard coal are imported at exogenously set prices, based on the assumption that Germany acts as a price taker. This appears reasonable as the amount of fossil energy carriers used in Germany is relatively small compared to global volumes. Albeit hard coal and natural gas are also extracted domestically, these sources are neglected in REMIND-D. The reason is that the amount of natural gas extracted domestically is too small to make explicit modeling worthwhile. Shale gas is not considered. Hard coal mining is heavily subsidized, which will be phased-out until 2018. Table 6 reports the import price paths for the standard setting in REMIND-D.

Table 6: Import prices of fossil primary energy resources in €$_{2005}$ per GJ. Oil, natural gas and hard coal prices are from BMU (2008) Scenario "Maessig", uranium prices are from Du and Parsons (2009).

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Oil	7.51	8.66	9.56	10.54	11.52	12.49	13.29	14.08	14.60	15.12
Nat. Gas	4.66	6.92	7.65	8.43	9.22	9.99	10.63	11.26	11.68	12.10
Hard Coal	2.10	3.46	3.82	4.22	4.61	5.00	5.32	5.63	5.84	6.05
Uranium	0.45	0.50	0.59	0.71	0.84	1.00	1.18	1.41	1.67	1.99

Lignite is exclusively mined and consumed domestically, so we use an extraction cost curve approach in REMIND-D. The price of lignite rises with the cumulative extraction, which is limited to 6.1 Gt. This number corresponds to the amount of lignite that may still be extracted from already active open cast mines (DEBRIV 2009). Reserves are larger in Germany, but opening new mines will most likely be impeded by public protest.

The use of exhaustible fossil energy carriers leads to CO_2 emissions, whereby the application of Carbon Capture and Storage (CCS) technologies may contribute to significant reductions. Conversion technologies using biomass may also be used in combination with CCS, here it is possible to incur "negative" CO_2 emissions as biomass captures CO_2 from the atmosphere.

Nuclear energy is a highly controversial political topic in Germany. The atomic energy law (AtG) in Germany has undergone three major revisions in the past ten years. In 2002, the law was changed to ensure a nuclear phase-out until around the year 2020. In 2010, the law was revised to postpone the phase-out until around 2050. However, after Fukushima, the government decided in August 2011 to close down eight nuclear power plants immediately and subsequently decommission the remaining ones until 2022. In REMIND-D the nuclear phase-out according to AtG2011 is implemented.

4.2 Characteristics of Technologies

Main Input Each technology is assigned a main input energy carrier.

Other Input In case a technology needs some additional input for its process, this input is represented by means of a fixed input coefficient.

Main Product Each technology is assigned a main output.

Couple Product Some technologies inherently produce couple products in their process. In case their energetic share is not negligible, they are modeled by means of fixed couple product coefficients that relate the energetic couple product output to the main output.

Conversion Efficiency The conversion efficiency of a technology determines the ratio between energy input and output. Technologies that are considered to be technically mature have a constant conversion efficiency over time. Technologies that are expected to be refined in the future have time-dependent conversion efficiencies.

Capacities Historical capacity additions that have taken place in Germany since 1930 are an input to the model. Each vintage has a specific conversion efficiency. Over the optimization period, the stock of installed capacity is increased by investments and decreased when capacities reach the end of their technical lifetime.

Technical Lifetime Each technology is assigned a specific technical lifetime (TLT). Capacities built up in a certain time step t exist and produce output until the time step $t + TLT$. Optionally, lignite and coal power plants are exempted.

Full Load Hours Installed generation capacities produce output only in a fraction of the entire year due to maintenance or physical constraints. Hence, each technology has a characteristic full load hour ratio that relates the number of producing hours to the total hours in a year. For existing technologies, this number is derived from empirical observations. For renewable energies a discrete grade structure

that differentiates between sites of different quality is implemented. For transport technologies this parameter is to be interpreted as person-km or ton-km per vehicle per year. For electricity generating technologies, the full load hours are endogenous to REMIND-D from 2010 onwards. Details on this issue are in Ueckerdt et al. (2011).

Investment Costs Building up capacities of a technology incurs investment costs. Each technology te is assigned a specific turnkey investment cost $in_{t,te}$ in €/kW, derived from the technical literature. Equation 5 defines the total investment costs IN_t incurred in a respective time step t, depending on the capacity additions $\Delta cap_{t,te}$.

$$IN_t = \sum_{te} (in_{t,te} \cdot \Delta cap_{t,te} + \gamma_{te} \cdot adj_{t,te}) \quad \forall t, te \tag{5}$$

For mature technologies, the specific investment costs are constant over time; for learning technologies they can decrease due to learning-by-doing effects. To prevent the model exhibiting excessively large expansion rates in a certain time step, investment costs are potentially increased by technology-specific adjustment cost $adj_{t,te}$, scaled with a scaling coefficient γ_{te}, set to 0.4. Adjustment costs are a means to increase model realism.

Learning Technologies For some technologies specific investment costs are expected to decrease with the cumulative installed capacity, according to the concept of "Learning by doing". In REMIND-D, a modified one-factor learning curve concept is used that is summarized in Equation 6, determining the specific investment costs, $in_{t,te}$, for the subset of learning technologies $tel \subset te$.

$$in_{t,te} = \alpha \cdot capcum_{t,te}^{\beta} + inF_{te} + inG_{t,te} \quad \forall t, tel \subset te \tag{6}$$

$$\alpha = \frac{in_{2005,te} - inF_{te}}{in_{2005,te}^{\beta}}$$

$$\beta = \frac{in_{2005,te}}{in_{2005,te} - inF_{te}} \cdot \frac{\ln(1 - l_{te})}{\ln 2}$$

Especially for onshore and offshore wind as well as solar photovoltaic, the domestic cumulative installed capacity $capcum_t$ is expected to have only an impact on local components of the specific investment costs, like fundaments, grid connections, or assembly. Hence, the specific investment costs for these three technologies are split into an initial local component $in_{2005,te}$, that exhibits cost decreases with a learning rate l_{te} up to a certain floor cost inF_{te}, and a global component $inG_{t,te}$ that experiences cost decreases on an international level and represents the solar panel or the generator for wind turbines. For learning technologies other than wind and solar photovoltaic it is assumed, that domestic capacities are the dominant driver for investment costs.

Adjustment Costs To prevent the model from exhibiting excessive expansion rates that would not occur in the real world due to inertia and general bottlenecks, adjustment costs are implemented. The idea of adjustment costs is to force the model into more gradual expansion paths by punishing fast increases and decreases of relative capacity additions with scaled monetary costs $adj_{t,te}$ that are specific for each technology and depend on the relative capacity additions between two subsequent years. Equation 7 shows the functional relationship.

$$adj_{t,te} = \frac{(\Delta cap_{t-1,te} - \Delta cap_{t,te})^2}{\Delta cap_{t-1,te} + \epsilon_{te}} \quad \forall t, te \tag{7}$$

For each technology, a specific capacity threshold ϵ is defined, representing an estimate of realistic capacity additions, based on past observations. For any capacity increase beyond the threshold, adjustment costs would be incurred and thereby increased the specific investment costs for a specific technology in a specific year. However, the model minimizes adjustment costs to a negligible level and instead smoothens the expansion paths. So the concept is rather theoretical and a means to increase model realism.

Operation and Maintenance Costs Besides investment cots, each technology incurs variable and fixed operation and maintenance costs (O&M costs) retrieved from the technical literature. Fixed O&M costs, omf_{te}, are defined in €/kW for each technology; variable O&M costs, omv_{te} in €/MWh. Equation 8 shows how total O&M costs, OM_t, in a respective year t are determined by the installed capacities $cap_{t,te}$ and amount of main product $MP_{t,te}$ for each technology te.

$$OM_t = \sum_{te} (omf_{te} \cdot cap_{t,te} + omv_{te} \cdot MP_{t,te}) \quad \forall t, te \tag{8}$$

Fuel Costs Fuel costs are incurred by those technologies that need costly primary energies as an input. These are hard coal, lignite, natural gas, uranium and biomass; price paths are discussed in Section 4.1. Total fuel costs FU_t in a respective time step are determined by the primary energy demand of a technology $d_{t,te,PE}$ multiplied with the price of the primary energy $p_{t,PE}$.

$$FU_t = \sum_{te,PE} (p_{t,PE} \cdot d_{t,te,PE}) \quad \forall t, te \tag{9}$$

Energy System Costs Total energy system costs E_t in a respective time step t are depicted in Equation 10. They need to be covered by the GDP in each time step. This is the monetary part of the hard link between the energy system and the macroeconomic module in REMIND-D.

$$E_t = IN_t + OM_t + FU_t \qquad \forall t \tag{10}$$

4.3 Conversion Technologies

4.3.1 Primary to Secondary Energy

An overview of the PE→SE conversion technologies and their acronyms is given in Table 7. The respective abbreviations are reported in Table 8. Missing in this overview is, due to space constraints, the Thermal Nuclear Reactor (TNR) that converts uranium into electricity, ethanol production from Biomass Sugar&Starch (BioSS-ETN) and diesel production from Biomass Oil (BioO-DIE). In case technologies appear in several fields, this indicates that they are subject to co-production. A prominent example is combined heat and power. Co-production occurs also to a lesser extent with other technologies, yet for the sake of readability they are not considered in the overview table. As becomes evident, hard coal, lignite and lignocellulose are very flexible primary energy carriers as they permit the production of almost all types of secondary energy carriers. Renewable energy sources are especially applicable for producing electricity. The secondary energy carriers electricity, hydrogen, gas, district heat, coke and petrol are as such usable for an end-consumer once distributed to the place of consumption. Middle distillate is an intermediate product. The secondary energy local heat is a pseudo-energy carrier as local heat is generated at the place of consumption.

The structure of Table 7 is suggestive of a set of balance equations that relate the primary energy demand to secondary energy production via conversion efficiencies and full load hours on the technical side. On the economic side each technology has specific investment, variable and fixed maintenance costs and a technical lifetime. These parameters are presented in the following for each technology, organized by secondary energies that are the main product. The data is based on the referenced technical literature and represents best available technique values in most cases.

Electricity and District Heat All non-fluctuating electricity generation technologies' techno-economic parameters are reported in Table 9. Lig-PC and Coal-PC are conventional coal power plants with the highest CO_2 emission intensity of all electricity generating technologies. A minor improvement constitutes the construction of PC+ power plants, supercritical coal power plants that achieve a higher conversion efficiency. A combination with the Carbon Capture and Sequestration (CCS) technology allows for severely (80-90%) reducing the CO_2 emissions intensity but still use coal as a primary energy source, which could be of interest for the domestic lignite resources and considering the abundant global hard coal resources. Coal-PC/CCS and Lig-PC/CCS represent the post-combustion technology that separates the CO_2 from the flue gas in a chemical process after conventionally burning the pulverized coal. Two more CCS technologies are considered: Oxyfuel (PC/CCS-O) and Pre-Combustion (IGCC/CCS). The Oxyfuel process is different as the coal is burnt in an atmosphere that consists of re-circulated flu gas enriched with pure oxygen. Through the re-circulation process, the flu gas eventually consists to a very large extent of CO_2 and can conveniently be processed further.

Table 7: Overview of the primary to secondary (PE→SE) energy conversion technologies represented in REMIND-D.

Secondary Energy Carriers	**Primary Energy Carriers**					
	Hard Coal	Lignite	Gas	BioLC	BioM	RES
Electricity	Coal-PC Coal-PC+ Coal-PC/CCS Coal-PC/CCS-O Coal-IGCC/CCS Coal-CHP	Lig-PC Lig-PC+ Lig-PC/CCS Lig-PC/CCS-O Lig-IGCC/CCS Lig-CHP	Gas-TUR Gas-CC Gas-CC/CCS Gas-CHP	BioLC-COM BioLC-CCHP BioLC-GCHP BioLC-IGCC BioLC-IGCC/CCS	BioM-CHP	Solar-PV Wind-OFF Wind-ON Geo-HDR Hydro
Hydrogen	Coal-H2 Coal-H2/CCS	Lig-H2 Lig-H2/CCS	Gas-SMR Gas-SMR/CCS	BioLC-H2 BioLC-H2/CCS		
Gas	Coal-GAS	Lig-GAS	Gas-TR	BioLC-GAS	BioM-GAS	
District Heat	Coal-HP Coal-CHP	Lig-HP Lig-CHP	Gas-HP Gas-CHP	BioLC-HP BioLC-CCHP BioLC-GCHP	BioM-CHP	
Coke	Coal-COK					
Petrol				BioLC-ETN		
Middle-distillate	Coal-TL Coal-TL/CCS	Lig-TL Lig-TL/CCS		BioLC-TL BioLC-TL/CCS		
Local Heat						Solar-TH Geo-HPU

Table 8: Abbreviations in alphabetical order.

CC:	Combined Cycle	IGCC:	Integrated Gasification CC
CCHP:	Combustion with CHP	OFF:	Offshore
CCS:	Carbon Capture and Storage	ON:	Onshore
CHP:	Combined Heat and Power	PC:	Pulverized Combustion
COK:	Coking	PC+:	Supercritical PC
ETN:	Ethanol production	PV:	Photovoltaik
GAS:	Gasification	SMR:	Steam Methane Reforming
GCHP:	Gasification with CHP	TH:	Thermal Hot Water Generation
H2:	Hydrogen Production	TL:	Liquefication
HDR:	Hot-Dry-Rock	TR:	Transformation
HPU:	Heat Pump	TUR:	Turbine

Post-combustion achieves higher removal rates. The Pre-Combustion technology relies on the gasification of coal in a first step and then separates the CO_2 before combusting the hydrogen-rich synthetic gas in a gas turbine. In the model, separated CO_2 enters a stylized CCS-Chain that represents a CO_2-pipeline infrastructure and sequestration sites. The compression of CO_2 for sequestration requires electricity, the losses in this process are accounted for by reducing the conversion efficiency of the technologies facilitating CCS.

Apart from supercritical or CCS power plants, the combined heat and power (CHP) technology constitutes a mitigation option. In a CHP plant, the waste-heat is recycled by flowing through a district heat network and is used for warm water and heating in households or industry. A CHP plant can either produce heat or electricity as a main product. In Germany, they are generally producing more heat than electricity. In the extreme case of producing only district heat, they are then simply heat plants (HP).

Electricity generation from natural gas has the technical advantage over coal that gas power plants are able to ramp up and down within very short time scales and hence are a good complement to fluctuating RES, especially valid for gas turbines (Gas-TUR). Gas-TUR have the characteristic of very low specific investment costs but high fuel costs as conversion efficiencies are moderate and Gas is a relatively expensive primary energy carrier. Combined cycle plants (Gas-CC) have significantly higher conversion efficiencies, but are less flexible. They may also be constructed with post-combustion CCS, yet this option is more costly and possesses an even lower degree of flexibility. Electricity production from natural gas has approximately half the CO_2 emission intensity than from lignite and as such presents itself as a mitigation option. From a geopolitical point of view, the increased dependence on natural gas would make Germany more dependent on supply countries. A major possibility for domestic gas supply could be the methanation of hydrogen produced during temporary overproduction of electricity by RES; this option is not yet included into REMIND-D but work is in progress.

Lignocellulose is currently combusted for either only power generation (BioLC-COM), both heat and power (BioLC-CCHP) or only heat (BioLC-HP). Gasification of lignocellulosic biomass is a future technology that is still in a demonstration phase but may become very attractive in the future, both for co-generation (BioLC-GCHP) and sole electricity production (BioLC-IGCC). The latter may also be combined with CCS, it would then be possible to not only be CO_2 emission-neutral, as is the case for all BioLC technologies, but even create negative CO_2 emissions. The BioMCHP technology relies on manure that is being mixed with some parts of Sugar and Starch Biomass (BioSS) for achieving an anaerobic gasification. After cleaning this gas it is used with a normal burner and turbine to produce heat and power. Hydro represents a standard running water hydropower plant and Geo-HDR the production of electricity from hydrothermal resources. The full load hours reported are an average, as a discrete grade structure distributes the potential to slightly different quality sites with differing full load hours. DOT refers to a diesel oil turbine, which is actually a SE→SE technology, but is included into this overview table.

Table 9: Techno-economic parameterization of (PE→SE) energy conversion technologies represented in REMIND-D, that produce electricity or heat as main product and are non-fluctuating technologies. Full load hours are empirical values of 2007 and are only fixed in the first time step of REMIND-D. Sources: Hake et al. (2009), Schlesinger et al. (2010), IEA (2010), Bauer et al. (2009), MIT (2007), EC (2006),Nitsch et al. (2004), Schulz (2007), Konstantin (2009a),Konstantin (2009b), Thrän et al. (2009), BMU (2008), own calculations.

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Variable Costs €$_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
Coal-PC	45	1150	22	6.85	44	6830
Coal-PC+	40	1800	36	7.99	50	6830
Coal-PC/CCS	45	1800	29	11.41	38	6830
Coal-PC/CCS-O	40	1900	34	13.7	41	6830
Coal-IGCC/CCS	40	2000	44	13.7	42	6830
Coal-CHP	40	430	9	4.57	$62_{th}/24_{el}$	5000
Coal-HP	45	350	11	2.76	93_{th}	4290
Lig-PC	45	1300	22	9.13	43	7000
Lig-PC+	40	1600	27	7.99	48	7000
Lig-PC/CCS	45	2100	29	14.84	35	7000
Lig-PC/CCS-O	40	2200	35	17.12	39	7000
Lig-IGCC/CCS	40	2300	46	17.12	40	7000
Lig-CHP	40	530	11	5.14	$57_{th}/18_{el}$	5700
Lig-HP	50	400	12	2.76	91_{th}	6750
Gas-TUR	30	300	9	1.84	32	1750
Gas-CC	35	500	30	0.53	55	1750
Gas-CC/CCS	35	850	34	1.87	51	1750
Gas-CHP	35	380	23	0.34	$50_{th}/30_{el}$	5000
Gas-HP	45	240	7	1.84	95_{th}	7890
BioLC-COM	40	2200	77	6.19	27	7010
BioLC-CCHP	40	3700	130	3.80	14	5960
BioLC-GCHP	40	4000	140	2.77	38	5960
BioLC-IGCC	40	1500	60	2.89	42	7010
BioLC-IGCC/CCS	40	2061	82	4.64	31	7010
BioLC-HP	40	450	12	1.20	85_{th}	4990
BioM-CHP	40	2700	135	1.70	38	7010
Hydro	80	5000	100	-	100	4820
Geo-HDR	35	4427	177	-	100	8000
DOT	40	322	10	0.92	30	800

Table 10: Techno-economic parameterization of the fluctuating learning technologies Sol-PV, W-OFF and W-ON. The first number given for investment costs refers to the local share, the second number to the global share. Floor costs and learning rates apply only to local components. The model takes the sum of both numbers as investment costs in each year. Sources: Neij et al. (2003), Nitsch et al. (2004), Junginger et al. (2004), Junginger et al. (2008), Konstantin (2009a), Schiffer (2008), Vrijmoed et al. (2010), own calculations.

	TLT	Investment Costs (in 2005)	Floor Costs	Learning Rate	Cumulated Installed Capacity (in 2007)	Fix Operating Costs
	Year	€$_{2005}$/kW	€$_{2005}$/kW	%	MW	€$_{2005}$/kW
Sol-PV	25	1600+2400	420	20	3811	40
W-ON	35	350+830	280	12	22247	22
W-OFF	25	1500+1000	580	25	0.001	125

Table 11: Development path of the exogenous global learning component in €$_{2005}$/kW. The data is retrieved from a REMIND-R 2° scenario.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sol-PV	2400	1459	1070	856	728	655	602	560	527	500
W-ON	828	705	627	602	589	583	578	573	570	566
W-OFF	1000	949	818	753	722	707	698	692	688	685

Fluctuating RES include Solar-PV, Wind-OFF and Wind-ON; their techno-economic parameters are reported in Table 10. They are implemented as learning technologies by means of the learning-by-doing approach, as described in Section 4.2. The idea is that the specific investment costs of these RES will decrease in the future due to cost efficiency developments in production and deployment with increasing installed capacities. As learning-by-doing effects operate on the global scale one cannot use exclusively German installed capacities for extrapolating future cost decreases. For all three technologies, some parts of the specific capital investment costs are related to local components, such as building the fundament or the grid connection of a solar panel or wind turbine. Such experiences have to be made within one country and domestic installed capacity is a good proxy driver for local components' cost reductions. However, the solar panel or the wind turbine's generator may be traded internationally and here global installed capacities' are an appropriate driver. The techno-economic parameterization for the fluctuating learning components is illustrated in Table 10. The development path of the global investment costs components are shown in Table 11, derived from a REMIND-R 2° scenario.

Table 12: Techno-economic parameterization of the primary to secondary (PE→SE) energy conversion technologies represented in REMIND-D that have hydrogen (H2) or gas as a main product. Sources: Yamashita and Barreto (2005), Gül et al. (2007), Hamelinck (2004), Nitsch et al. (2004), own calculatios

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Variable Costs €$_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
Coal-H2	50	1020	31	0.42	59	7000
Coal-H2/CCS	50	1150	35	0.49	57	7000
Lig-H2	50	1015	31	0.42	57	7000
Lig-H2/CCS	50	1150	35	0.49	55	7000
Gas-SMR	45	400	12	12.70	73	7890
Gas-SMR/CCS	45	445	13	16.91	70	7890
BioLC-H2	45	1127	113	0.97	61	7880
BioLC-H2/CCS	45	1368	137	0.97	55	7880
Elec.-H2	17	241	12.05	0.25	62	7880
Coal-GAS	50	725	22	0.38	60	4800
Lig-GAS	50	725	22	0.38	58	7000
BioLC-GAS	40	2817	141	1.38	55	7450
BioM-GAS	40	2415	121	1.10	60	7450

Hydrogen and Gas The techno-economic parameterization of technologies producing gaseous secondary energy carriers are displayed in Table 12. Currently, hydrogen is mainly used for chemical processes but not as a source of energy. However, it could potentially be useful in the future for delivering process heat to industry or as fuel in nonstationary appliances like cars and buses. Conventional technologies for producing hydrogen is steam metane reforming (SMR) from natural gas and electrolysis, which is a SE→SE technology. SMR can also be coupled with CCS, then the hydrogen production would be almost carbon neutral. Other possible technologies for producing hydrogen include converting hard coal, lignite or lignocellulosic biomass first into synthetic gas and then into hydrogen, both with and without CCS.

Gas is currently imported to a large extent in the form of natural gas obtained from drilling. Yet this primary energy carrier could also be produced by the gasification of hard coal, lignite and lignocellulotic biomass. Under the EEG scheme, the production of biogas by fermentation of manure with grass or maize silage has been subsidized, hence, recently several biogas plants started operating in Germany (Thrän et al. 2009).

Liquids and Others The vast majority of fuels for transport was produced from fossil crude oil in 2007. REMIND-D features a refinery sector that is explained in detail in

Table 13: Techno-economic parameterization of the primary to secondary (PE→SE) energy conversion technologies represented in REMIND-D, that have raffinate, diesel, petrol, coke or local heat as a main product. Sources: Krey (2006), Yamashita and Barreto (2005), Gül et al. (2007), Hamelinck (2004), Ragettli (2007), Tijmensen et al. (2002), Nitsch et al. (2004), own calculatios

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Variable Costs €$_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
ATDES	30	37	3.7	0.13	53	7880
Coal-TL	50	805	40	0.38	40	7450
Coal-TL/CCS	50	840	46	0.38	40	7450
Lig-TL	50	805	40	0.38	38	7450
Lig-TL/CCS	50	840	46	0.38	38	7450
BioLC-TL	45	2012	80	0.97	40	7970
BioLC-TL/CCS	45	2415	97	0.97	41	7970
BioO-DIE	45	104	5	0.46	93	7880
BioSS-ETN	45	394	45	3.58	55.3	7920
BioLC-ETN	45	1918	125	8.94	36.3	7920
Coal-COK	40	240	12	0.38	80	5250
Solar-TH	25	1127	34	-	100	867
Geo-HP	35	1610	48	-	100	4380

Section 4.3.2 as it conceptually belongs to the class of secondary to secondary energy conversion technologies. The first step in a refinery is the atmospheric distillation (ATDES), in which the crude oil goes through a fractional distillation at atmopspheric pressure. The main output of the ATDES process is raffinate, couple production yields 34.45% of middle distillate, 10.60%of petrol and 1.60% of heavy fuel oil. The gaseous fraction is neglected as it is only a small energetic fraction and often the refinery gas, at it is called, is re-used in the refinery itself for heating purposes in the distillation processes. Middle distillate is further refined to petrol, diesel or heating oil and can also be produced from hard coal, lignite or lignocellulosic biomass.

Due to several incentive schemes, biofuels had a minor share of 8% for diesel consumption and 2% for petrol consumption in Germany in 2007. Biosynthetic diesel can be directly produced from oily biomass, mainly rapeseed oil in Germany, by means of transesterification with methanol (BioO-DIE). Ethanol is produced from sugar and starch biomass (BioSS-ETN) and admixed recently with 5% to the standard petrol. Liquefaction of lignocellulosic biomass is known under the keyword second-generation biofuel production

and may become a viable large-scale production of biofuels that is not subject to ethical problems in the future. On the contrary, oily as well as sugar and starch biomass may be used as food instead of energetic use, which leads to severe political discussions in Germany.

Other PE→SE technologies are the coking process that produces coke from hard coal that is mainly used in steel production and heat pumps for domestic use. As already mentioned, heat pumps produce local heat at the residential place of consumption. They use electricity as input, besides the solar thermal or low-pressure geothermal potential.

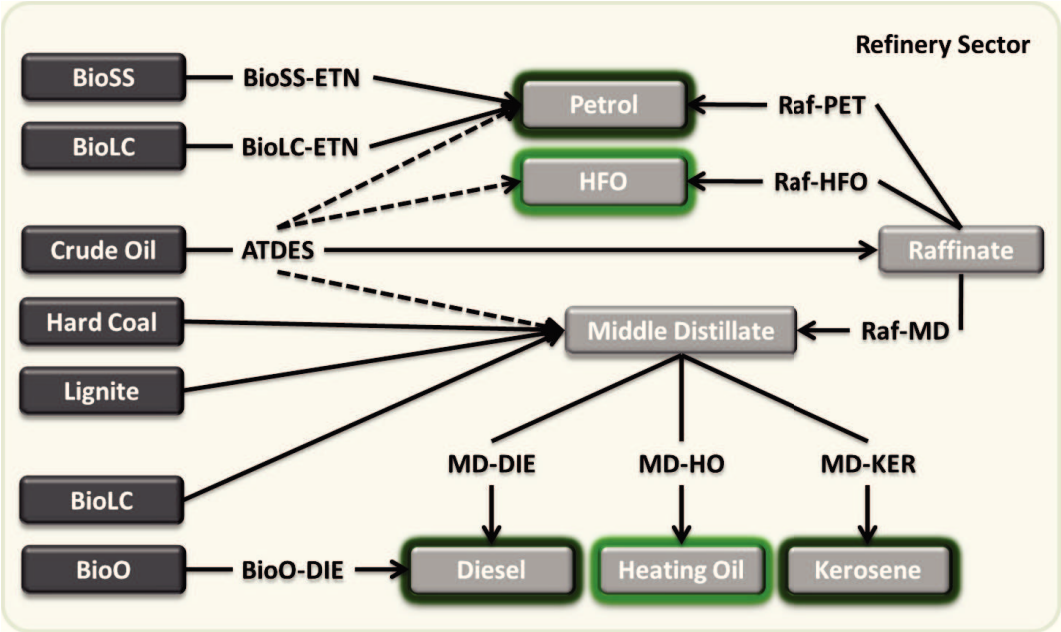
4.3.2 Secondary to Secondary Energy

Apart from the technologies electrolysis and diesel oil turbine, that were already discussed in the last section, the refinery sector is implemented as a set of SE→SE-technologies as illustrated in Figure 5. It is modeled in a stylized way to represent the complexity of a real-world refinery and permit the necessary degrees of freedom regarding the output mix. The first step in the conventional refinery process is the atmospheric distillation (ATDES), that produces raffinate as a main product, with fixed couple production of petrol, middle distillate and heavy fuel oil (HFO), as discussed in the last section. Raffinate and middle distillate represent intermediate products, that are further processed into usable fuels. The respective technologies have short technical lifetimes of 10 years, so the refinery sector does not per se dictate the model the fuel mix used in the transport sector. Raffinate may be converted in Petrol or HFO with the technologies Raf-PET and Raf-HFO, these technologies represent the vacuum distillation in a real-world refinery. Middle Distillate may be converted into diesel (MD-DIE), Heating Oil (MD-HO) or Kerosene (MD-KER). The techno-economic parameterization of these technologies is derived from aggregation of the very detailed refinery representation in Krey (2006) and reported in Table 14

Table 14: Techno-economic parameterization of the intermediate refinery processes. Sources: Krey (2006), MWV (2008), own calculatios

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Variable Costs €$_{2005}$/MWh	Conv. Eff. %	Full Load h/pa
Raf-PET	10	157	7.85	0.504	90	7880
Raf-HFO	10	41	2.05	0.104	90	7880
Raf-MD	10	134	6.70	0.447	90	7880
MD-KER	10	24	1.20	0.919	90	7880
MD-HO	10	16	0.80	0.919	90	7880
MD-DIE	10	8	0.40	0.919	90	7880

Figure 5: The refinery sector in REMIND-D. Dashed arrows indicate couple production. Abbreviations are explained in the text.



As has been discussed in the last section, to substitute the crude oil in the fuel production process, Middle Distillate may also be produced from hard coal, lignite or lignocellulose by means of liquefaction. Furthermore, Diesel may be produced from oily biomass and petrol may be produced from sugar and starch (first-generation biofuels) or lignocellulose (second-generation biofuels).

4.4 Distribution Technologies

In the single region model REMIND-D, distribution technologies are a means of representing distribution networks and infrastructure requirements in a parameterized way, since the spatial dimension is not applicable. Table 15 presents the considered technologies and their acronyms, Table 16 the techno-economic parameterization.

The distribution technologies capacities are expressed in capacity per energy unit of energy carrier that needs to be distributed. For the RES&COM sector, the distribution is generally more costly than for the IND sector, as distribution networks need to be highly branched. For the transport sector, the distribution technologies consider the fuel station network. In the model, the existing distribution technologies need not necessary to be used at full capacity to prevent the phenomenon that they dictate the choice of final energies or energy services in climate policy scenarios.

Table 15: Overview of the distribution technologies in REMIND-D.

Secondary Energy Carriers	Industry	RES&COM	Transport
Natural Gas	D_Gas-IND	D_Gas-RES&COM	D_Gas-Trans
Electricity	D_El-IND	D_El-RES&COM	D_El-Trans
District Heat	D_DHeat-IND	D_DHeat-RES&COM	
Heating Oil	D_HeatOil-IND	D_HeatOil-RES&COM	
Local Heat		D_LHeat-RES&COM	
Coke	D_Coke-IND		
HFO	D_HFO-IND		
H2	D_H2-IND		D_H2-Trans
Petrol			D_Pet-Trans
Diesel			D_Die-Trans
Kerosene			D_Ker-Trans

Natural gas networks consist of major long-distance pipelines and local distribution infrastructure, especially for the RES&COM sector. For the transport sector is assumed that only the fuel-filling infraststructure and the access to the pipeline-system is required additionally and existing gas stations can be retrofitted. Electricity grids in Germany exist in three different formats: maximum voltage (220 or 380 kV), medium voltage (6 to 30 kV) and low voltage (240 or 400 V) and need to be extended for coping with a large share of RES in the system, which is necessary in climate policy scenarios. Of course, a proper representation of grids needs a fine geographical resolution in the energy system. In REMIND-D the expenses for electricity grids are approximated. For the electrification of the transport sector, eventually a network of charging stations is necessary. Since charging requires up to several hours, it is unlikely that the existing petrol station network may be the core of the future charging infrastructure. District heating networks are pipeline systems that are either under or above ground. Heating Oil and HFO is assumed to be transported with trucks and has very low upfront investment costs that represent the costs for special fuel trucks with short technical lifetimes. On the distribution of coke there is very little information available, it is assumed that coke is produced spatially close to the site of industrial consumption, so distribution costs are very small.

The built-up of a hydrogen network for delivering process heat for the industry sector required pipeline infrastructure. For the transport sector, not only the pipelines are needed, but also a retrofit of existing petrol stations with H2-filling devices. Due to fast fill-up of the tank, the existing petrol stations may be maintained. For petrol, diesel and kerosene the reasoning is similar as with heating oil - fuels are transported with fuel trucks to their place of consumption and upfront investment costs are low. The infrastructure of gas stations already exists and only needs to be maintained.

Table 16: Techno-economic parameterization of the distribution technologies represented in REMIND-D. Own calculations.

	TLT Year	Investment Costs €$_{2005}$/kW	Fix Costs €$_{2005}$/kW	Conv. Eff. %	Full Load h/a
D_Gas-IND	55	161	0.02	90	7010
D_El-IND	55	1006	0.10	97	7010
D_DHeat-IND	55	161	0.02	95	3500
D_HeatOil-IND	55	20	0	100	6570
D_HFO-IND	55	20	0	100	6570
D_Coke-IND	55	20	0.01	100	7880
D_H2-IND	55	241	0.02	100	7010
D_Gas-RES&COM	55	322	0.10	90	4380
D_El-RES&COM	55	1529	0.76	94	4380
D_DHeat-RES&COM	55	161	0.02	95	3500
D_HeatOil-RES&COM	55	40	0.02	100	4380
D_LHeat-RES&COM	55	0.0001	0	100	8760
D_Gas-Trans	55	161	0.02	90	7010
D_El-Trans	55	1500	0.08	100	6130
D_H2-Trans	55	241	0.12	100	5260
D_Pet-Trans	55	80	0.08	100	6130
D_Die-Trans	55	80	0.08	100	6130
D_Ker-Trans	55	80	0.08	100	6130

4.5 Transport Technologies

The transport sector, converting fuels to energy services in the form of spatial relocation of goods and passengers, is explicitly included in REMIND-D. To fulfill mobility requirements, conventional and innovative transport technologies of various modes are considered, see Table 17.

Long-distance passenger transport is provided by domestic aviation (Plane-KER), Intercity and ICE trains (Train-EL) and long-distance buses (Coach-DIE), as well as by motorized private transport (MPT). In Germany, a large share of the car fleet consists of diesel cars, which are characterized by somewhat higher upfront costs, but diesel is relatively less taxed than petrol. Consequently, those who need to frequently travel long distances choose diesel cars. Obviously, one can also travel short distances with diesel cars, as well, and vice versa one can travel long distances with petrol cars that are owned mainly for the purpose of short commuting. In REMIND-D, this fact is accounted for by defining a main purpose for a class of cars and then ensuring a second purpose techni-

Table 17: Overview of transport technologies in REMIND-D. Abbreviations are Hybrid (Hy), Plug-in Hybrid (PHy) and Fuel Cell (FC).

Secondary Energy Carriers	**Energy Services**		
	Passenger Long Distance (PLD)	Passenger Short Distance (PSD)	Freight (F)
Petrol		Car-PET Car-PET/Hy Car-PET/PHy	
Diesel	Car-DIE Car-DIE/Hy Coach-DIE	Car-DIE/PHy Train-DIE Bus-DIE Bus-DIE/Hy	Truck-DIE Train-DIE Ship-DIE
Natural Gas	Car-GAS Car-GAS/Hy		
Electricity	Train-EL	Car-EL Train-EL LightRail-EL	Train-EL
H_2		Car-H_2/Hy Car-H_2/FC Bus-H_2	
Kerosene	Plane-KER		

cally by means of 'couple production' of the transport technology. The classification of Table 17 reflects the main purposes of the respective transport technologies. For MPT transport, there are additionally various innovative car technologies. Local trains represent regional or medium-distance trains that either run on diesel or electricity. Inner-city public transport is covered by light rail trains and diesel, as well as innovative buses. The freight transport sector consists of trucks, trains and inland navigation.

Table 18 presents the techno-economic parameterization for all MPT car technologies with initial investment costs per car, fuel demand, yearly short- and long-distance performance and variable costs. Fixed costs are not considered as data is very case-specific and also scarce, especially for public transport and commercial trucking technologies. The investment costs of innovative car technologies can be reduced over time by two means: Technology-specific learning-by-doing by building up capacities or cluster-learning for batteries. For hybrid, plug-in hybrid and electric technologies, an increasing share of the specific investment costs is caused by the battery pack and related technology. In the battery sector, substantial cost reductions can be expected. As learning-by doing effects are occurring at a battery-level, the capacity additions of all technologies that use batteries are contributing to the learning. The investment costs for batteries are again

Table 18: Techno-economic parameterization of MPT technologies in REMIND-D. SD/LD indicates the yearly short/long-distance driving. Investment costs are split into chassis/drivetrain + battery-related costs, with the latter exhibiting cluster learning across all technologies. Car-H2/Hy and Car-H2/FC additionally have learning in the chassis/drivetrain investment costs by 6.7 and 13.8 Tsd.e, respectively, with a learning rate of 5%. Sources: Wietschel et al. (2010), Edwards et al. (2008b), Edwards et al. (2008a), Gül (2008), Kirchner et al. (2009), Krey (2006), own calculations.

	TLT Year	Investment Costs Tsd.€$_{2005}$ /car	Fuel Demand kWh /100 km	LD Tsd.km /a	SD Tsd.km /a	Variable Costs €$_{2005}$ /km
Car-ETN	12	19.5	68.00	2.4	9.6	0.027
Car-ETN/Hy	12	19.5+6.4	41.65	2.4	9.6	0.033
Car-ETN/PHy	12	19.5+8.1	44.90	2.4	9.6	0.073
Car-DIE	10	21.4	67.32	15.4	6.6	0.025
Car-DIE/Hy	10	21.4+6.4	38.61	15.4	6.6	0.030
Car-DIE/PHy	11	21.4+8.1	39.00	2.4	9.6	0.073
Car-GAS	12	21.6	52.00	17.6	4.4	0.027
Car-GAS/Hy	12	21.6+6.43	38.70	17.6	4.4	0.030
Car-H2/Hy	12	26.8+6.4	39.30	3.0	12.0	0.030
Car-H2/FC	12	33.3+1.6	23.30	3.0	12.0	0.075
Car-EL	10	19.6+17.7	15.00	0	15.0	0.099

split into a local and global component. In the future, the fuel demand of conventional car technologies is expected to follow the declining trend on a per 100km basis. Table 19 illustrates the techno-economic parameterization for the public transport technologies and Table 20 for the freight transport technologies

The dynamics of the transportation sector are very difficult to be represented in an energy system model that follows the logic of implicitly minimizing costs. For passenger transport, non-quantifiable factors such as minimizing travel time or maximizing travel comfort are frequently more influential for choosing a particular kind of transportation mode than pure cost calculations. Urbanization tendencies and general demographic developments do have an influence, too. In the case of motorized private transport (MPT) car owners often do not base their investment choices on clean cost calculations, but consider their car as fulfilling other purposes than just the technical transportation, e.g. status symbol, self-expression. As regards freight transport, the growth rate of transported ton-km has historically been very closely correlated to the growth rate of GDP (Feige 2007). As the underlying drivers of this link are rather complex, there is no direct link between GDP and freight transport volume in REMIND-D. In principle, they could become decoupled in the future, if the economy became more efficient in

Table 19: Techno-economic parameterization of public transport technologies in REMIND-D. The top panel displays technologies that serve short distance driving, the bottom one long distance driving. For Bus-H2, the 70Tsd.e are subject to learning with a rate of 5%. Sources: Krey (2006), Wietschel et al. (2010), own calculations.

	TLT	Investment Costs Tsd.€$_{2005}$ /vehicle	Fuel Demand kWh /100 km	Number of Passen-gers	Yearly Range Tsd. km /a	Fix Costs %	Variable Costs €$_{2005}$ /km
Bus-DIE	13	280	416	20	612	-	0.412
Bus-DIE/Hy	13	328	291	20	612	-	0.412
Bus-H2	13	280+70	400	20	612	-	0.405
Train-DIE	26	2270	1530	80	2960	0.02	1.9
Train-EL	26	2090	914	80	5600	0.02	1.8
LightRail-EL	26	2030	811	55	4125	0.02	1.8
Coach-DIE	13	280	240	25	875	-	0.412
Train-EL	26	16710	2100	223	66900	1.5	2.5
Plane-KER	17	22600	8000	115	28750	0.013	3.72

Table 20: Techno-economic parameterization of freight transport technologies in REMIND-D. Source: Krey (2006), own calculations.

	TLT	Investment Costs Tsd.€$_{2005}$ /vehicle	Fuel Demand kWh /100 km	Load Capa-city t	Yearly Range Tsd. km /a	Fix Costs %	Variable Costs €$_{2005}$ /km
Truck-DIE	10	33.6	225	5	125	-	0.0724
Train-DIE	27	3500	2780	434	30380	0.076	3.01
Train-EL	27	3700	1250	434	30380	0.05	3.02
Ship-DIE	47	2340	11000	918	24235	0.07	1.94

terms of transport-km per GDP. To account for these factors, the yearly total amounts of demanded ton-km and passenger-km for long- and short-distance travelling are part of the scenario definition in REMIND-D and are exogonous, if not explicitly stated otherwise. Without these constraints, the model has a tendency to severely decrease freight and short-distance passenger transport and increase long-distance passenger transport in the presence of a stricter CO_2 emissions budget. This can be easily understood from an energy-efficiency point of view, however, it does not reflect reality due to the missing non-quantifiable drivers in the model. Table 21 presents the assumed future developments in a standard setting.

Table 21: Assumed development paths of freight and passenger energy services demand. Source: Lenz et al. (2010).

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Freight	7.51	8.66	9.56	10.54	11.52	12.49	13.29	14.08	14.60	15.12

5 CO_2 Emissions

REMIND-D considers only CO_2 emissions from the energy sector that stem from the combustion of fossil fuels. The standard operating mode of REMIND-D is via a CO_2 emission budget over the entire optimizing time horizon. This method yields the maximum freedom for the model to allocate the emissions over time. REMIND-D can also be operated by implementing a specific CO_2 emission path or a CO_2 tax path. The CO_2 emission accounting in REMIND-D is implemented via the primary energy demand of CO_2-intensive energy carriers and their emission factors. These are 56 tCO_2/TJ for Gas, 72 tCO_2/TJ for Hard Coal, 113 tCO_2/TJ for Lignite and 72 tCO_2/TJ for Crude Oil (Strogies and Gniffke 2009). These are the emission factors used in the calculation of the Kyoto protocol reporting. All other primary energy carriers come without CO_2 emissions. In principle, the use of fossil and biomass energy carriers leads to CH_4, SO_x, NO_x emissions etc., which are, however, not considered in REMIND-D at the moment.

6 Model Validation

Validating causal-descriptive models that generate projections well into the future is an inherently challenging task. The concept of validity as such has been subject to a lengthy academic debate, strongly tied to philosophy of science issues. Barlas (1996) suggests that a model is valid if it demonstrates 'the right behaviour for the right reason'. Hence, a valid model produces results that are at once trustworthy, justifiable and meaningful for the problem under analysis. In fact, the validation of a model must be understood as a process, which is not separable from the modeling process itself (Landry et al. 1983). As a full-fledged validation exercise is beyond the scope of this document, this Section intends to give a brief indication of how model results obtained with REMIND-D relate to empirical data.

Figures 6, 7 and 8 display CO_2 emissions from energy use, GDP and final energy demand for Germany. Historical data is plotted together with model results from two scenario runs, for which the configuration of REMIND-D differs only with respect to the emission budget. Displayed model data are from two runs of the 'continuation' scenario, elaborated in Schmid and Knopf (2012). The 'Model Baseline' run achieves moderate 40% CO_2 emission reduction in 2050 relative to 1990, the 'Model Policy' run ambitious 88%.

Figure 6: German CO_2 emissions from energy use. Data from 1990-2009 are empirical (UBA 2010). Model results are obtained with REMIND-D for the years 2007-2050.

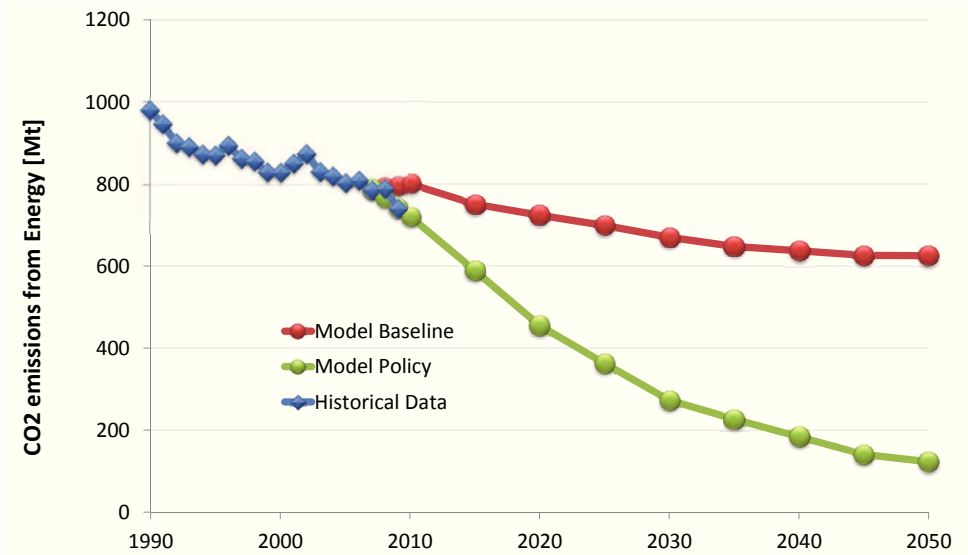


Figure 7: German Gross Domestic Product (GDP) in Bn €. Data from 1990-2009 are empirical (Statistisches Bundesamt 2012). Model results are obtained with REMIND-D for the years 2007-2050.

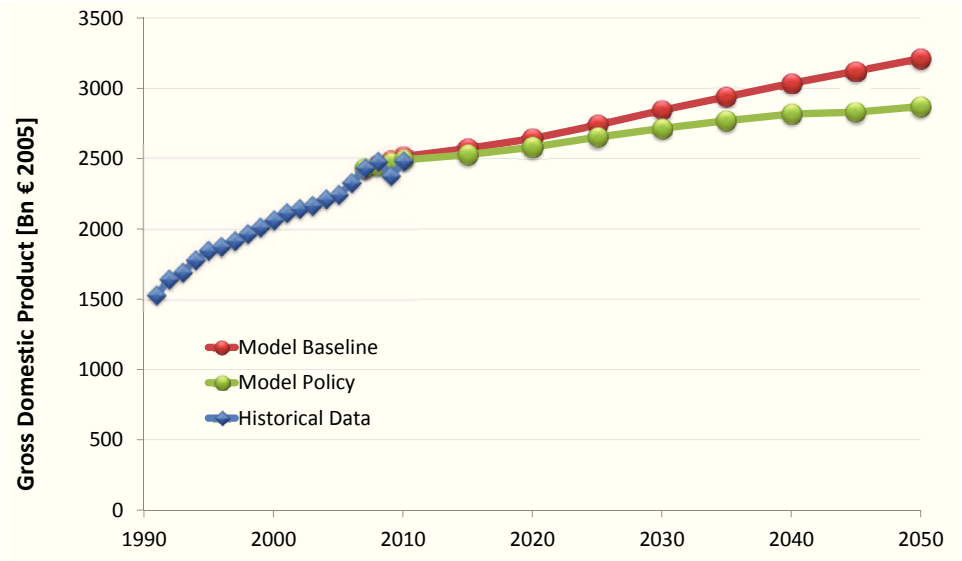
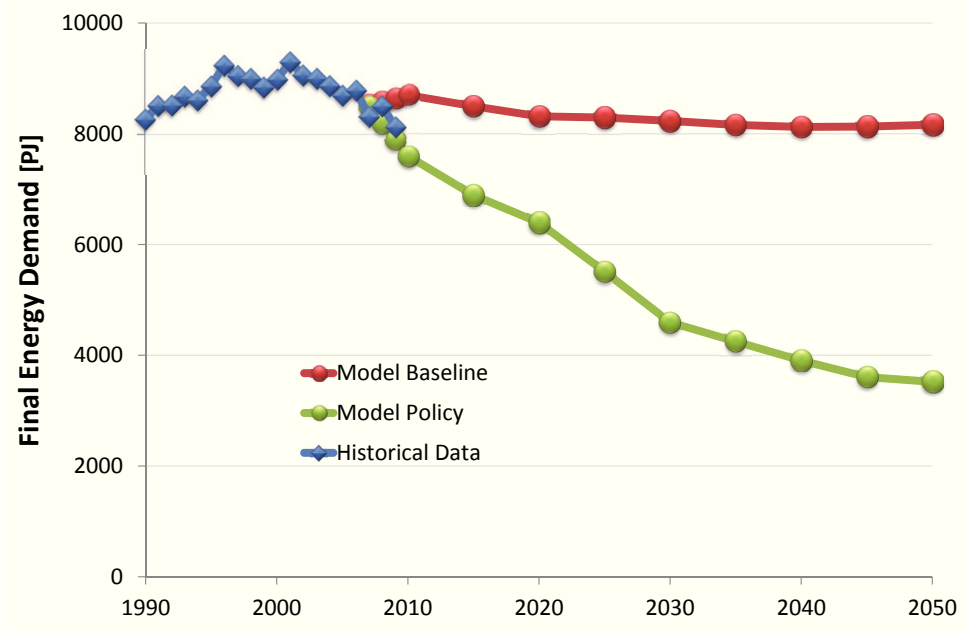


Figure 8: German final energy demand in PJ. Data from 1990-2009 are empirical(AG Energiebilanzen 2010). Model results are obtained with REMIND-D for the years 2007-2050.



The CO_2 emissions from the energy sector in the calibration year 2007 are reproduced well by the model results of REMIND-D. Since they are an outcome of the calibration procedure, the good fit is an indication for the validity of REMIND-D's structure. Interestingly, the empirical CO_2 emission in 2009 lie on the trajectory of the 'Model Policy' scenario, which leads to an ambitious mitigation mitigation target of 88% CO_2 emission reduction in 2050 relative to 1990. However, CO_2 emissions were particularly low in 2009 due to the financial crisis and it is unclear whether this trend continues. The 'Model Baseline' trajectory performs well in extrapolating the historical trend in emission reduction. GDP and final energy demand are reproduced by REMIND-D exactly in 2007 as they are a calibration input. GDP growth is slightly slower in the model results than observed historically. The reason why GDP trajectories are diverging between the two model runs is the additional and binding CO_2 budget constraint in the 'Model Policy' run. The historical trend in final energy demand is reproduced well by the 'Model Baseline' trajectory. Again, as is the case for total CO_2 emissions, the overlapping years 2007-2009 coincide with the 'Model Policy' data. A more extensive model validation, including the structured comparison between the results of REMIND-D and those of other models of Germany, will be addressed in future work.

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Chapter 4

Ambitious Mitigation Scenarios for Germany: A Participatory Approach *

Eva Schmid
Brigitte Knopf

*under revision in *Energy Policy*

Ambitious Mitigation Scenarios for Germany: A Participatory Approach

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Abstract

This paper addresses the challenge of engaging civil society stakeholders in the development process of ambitious mitigation scenarios that are based on formal energy system modeling, which allows for the explicit attachment of normative considerations to technology-focused mitigation options. It presents the definition and model results for a set of mitigation scenarios for Germany that achieve 85% CO_2 emission reduction in 2050 relative to 1990. During consecutive dialogues, civil society stakeholders from the transport and electricity sector framed the definition of boundary conditions for the energy-economy model REMIND-D and evaluated the scenarios with regard to plausibility and social acceptance implications. Even though the limited scope of this research impedes inferential conclusions on the German energy transition as a whole, it demonstrates that the technological solutions to the mitigation problem proposed by the model give rise to significant societal and political implications that deem at least as challenging as the mere engineering aspects of innovative technologies. These insights underline the importance of comprehending mitigation of energy-related CO_2 emissions as a socio-technical transition embedded in a political context.

Keywords: Social Acceptance, Stakeholder Dialogue, Energy System Modelling

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1. Introduction

Ambitious domestic mitigation efforts by Annex I countries are necessary for maintaining a likely chance to keep global warming below 2°C (UNEP, 2010). The European Union has committed itself to reduce CO_2 emissions by 20% in 2020 relative to those in 1990 (European Parliament and the European Council, 2009). Member states share the mitigation effort according to individual capabilities. This decision led Germany to target a 21% cut in domestic CO_2 emissions by 2020. In the long-term, the German Government endorses an ambitious target of 80-95% energy system related CO_2 emission reduction by 2050 relative to 1990 (Federal Government, 2010). Model-based mitigation scenarios that indicate how this transformation can be accomplished are a frequently demanded form of scientific policy advice.

As energy system modeling has traditionally been the domain of experts, particularly engineers, existing mitigation scenarios frame mitigation largely as a technology problem that can be solved by switching to innovative low-carbon technologies. For Germany, several model-based scenario studies have demonstrated that achieving the Government's long-term mitigation target will be technically feasible if best available technologies penetrate the market in large scale (e.g. Schlesinger et al., 2010; Nitsch and Wenzl, 2009; Nitsch et al., 2010; Kirchner et al., 2009). To achieve this, the studies suggest rigorous energy policy measures with far-reaching implications for the German society.

However, it was not subject of the analysis in these scenario studies whether their projected developments align with societal preferences. In case they do not align, social refusal to adopt or allow for the adoption of low carbon technologies may challenge ambitious mitigation targets. Indications that this is a real challenge in Germany are already observed. Local protest against the exploration of carbon sequestration sites contribute to the paralysis in the policy process for passing European legislation on carbon sequestration. Widespread refusal to use petrol with 10% biofuel additive (E10) endangers Germany's fulfillment of the European biofuel quota (MWV, 2011). Local opposition against the con-

struction of new power plants is considered as the most important market entry barrier for utilities (Deloitte, 2011). Further, local opposition against onshore wind farms, due to e.g. negative landscape externalities (Meyerhoff et al., 2010), have resulted in 40 negative out of 61 community referendums between 2009 and 2012 (Löhle, 2012).

Since public or local oppositions and other acts of societal refusal can severely delay the rapid and large-scale deployment of best available technologies, the notion of 'social acceptance' has become a keyword in the energy policy arena. Often, social acceptance is understood as something that can be established ex-post to investment or policy decisions by providing sufficient information to the public (e.g. Federal Government, 2010). However, attempts to explain acceptance and opposition in literature increasingly resort to procedural and institutional factors like beliefs, concern, place attachment, perceived fairness and levels of trust (Devine-Wright, 2008) which cannot be mediated by mere information campaigns. Rayner (2010) argues that the process of how a society chooses an energy future itself is as important for a socially, politically, economically and environmentally sustainable outcome as the availability of low-carbon technology options.

The Ethics Commission for a Safe Energy Supply, appointed by the Federal Government, corroborates that in order to ensure a high level of societal acceptance for the energy supply, transparency in the decisions made by both parliament and government as well as participation by societal groups in the decision-making process is a prerequisite (Ethics Commission for a Safe Energy Supply, 2011). Due to the decisive role that model-based mitigation scenarios can play as a form of scientific policy advice, the call for transparency and participation in their design and development process is valid accordingly. A further convincing argument for engaging societal groups that have a stake in energy system developments is that the choice of low-carbon technologies requires a wide range of normative considerations and value judgments for which science alone does not have a mandate.

For taking into account societal preferences, the German Academies of Sci-

ences advocate the application of 'analytical-deliberative' approaches (Renn et al., 2011) which originate in the field of risk management (e.g. Stern and Fineberg, 1996; Renn, 1999). Their notable trait is to provide a recursive linkage between the two discrete processes of analysis, the use of replicable methods developed by experts, and deliberation, the thoughtful weighting of options. A careful deliberation of mitigation options requires that direct and indirect implications of mitigation options are considered, discussed and reflected by the spectrum of affected stakeholders, collectively. In order to develop model-based mitigation scenarios that explicitly take into account stakeholders' judgments and preferences, they need to be elicited and translated to configurations of model input parameters. Model results then carry contextual, normative meaning and enable substantive discussions on the socio-political implications of technology-focused mitigation options. This can only be achieved in a participatory approach in which deliberation frames analysis and analysis informs deliberation.

Examples of participatory approaches to model-based mitigation scenarios are scarce in literature. The scenarios of the 'Roadmap 2050 for a low carbon economy' by the European Commission (2011) have been assessed on their impact through an online questionnaire which is a unilateral method only. The European Climate Foundation (ECF) periodically consulted a wide range of stakeholders throughout the preparation of mitigation scenarios for their 'Roadmap 2050' (ECF, 2010) but the concrete procedure is not described. To the authors' knowledge, there are no contemporary applications of participatory approaches to developing ambitious mitigation scenarios for Germany.

This paper aims to contribute in filling the gap by exploring a methodology for developing a set of model-based, long-term mitigation scenarios for Germany that are defined and evaluated in a participatory process with civil society organization (CSO) stakeholders from the transport and electricity sector. It addresses the domestic mitigation challenges not only from a techno-economic point of view but also from a socio-political perspective by combining both analytical and deliberative elements in a participatory methodology. The ex-

ploratory research was conducted as a part of the EU project ENCI LowCarb (Engaging Civil Society in Low Carbon Scenarios). Due to the pilot project character, the scenario results are to be interpreted as indicative of trends rather than being representative for the German civil society as a whole.

In dedicated stakeholder dialogues, CSO representatives discussed available mitigation options for the transport and electricity sector. Their judgments and preferences framed the scenario definition and corresponding parameter configurations for the hybrid energy-economy model REMIND-D (Schmid et al., 2012a). REMIND-D is based on the structural equations of the state-of-the-art global Integrated Assessment Model (IAM) REMIND-R (Leimbach et al., 2010). Since REMIND-D is a hybrid model, integrating a detailed bottom-up energy system module into a top-down representation of the macro economy, the scenarios can be analyzed both with respect to their technological and economic feasibility. In a second round of dialogues, stakeholders evaluated the plausibility of the scenarios and identified potential socio-political implications of the model-based mitigation scenarios.

The outline is as follows: Section 2 presents the methodology. Section 3 discusses the outcomes of the participatory scenario definition process. Section 4 guides through the scenario results obtained with REMIND-D, focusing on structural trends in the development of CO_2 emissions by sector, modal splits in the freight and passenger transport sector and the electricity generation mix. Mitigation costs, along with a sensitivity analysis on how they depend on the stringency of the mitigation ambition, are presented in Section 4.4. Section 5 reports the CSO stakeholders' evaluations of the mitigation scenarios. Section 6 summarizes and concludes.

2. Methodology

The objective of this research is to develop ambitious mitigation scenarios for Germany that integrate both techno-economic and socio-political dimensions of the domestic mitigation challenge. In order to build a bridge between

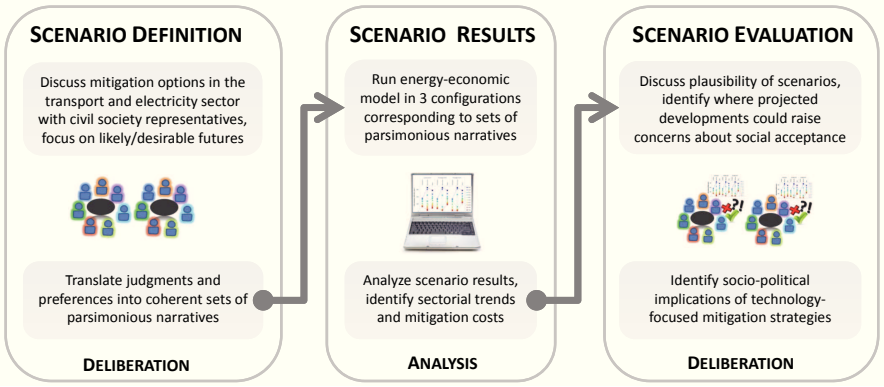

Figure 1: Stylized overview of the applied methodology

the two, the specific requirements on the research team go beyond pure expertise on energy-economy modeling and call for project partners that are well embedded in the civil society sphere. Thus, the core research team consisted of both non-governmental organization (NGO) partners and researchers that collaborated closely throughout the project. The participatory scenario definition and evaluation process illustrated in this paper was preceded by an intense preparatory phase in which the interdisciplinary research team developed a joint understanding of how stylized model parameters and results may be translated into real-world implications and vice versa. Details on this preparatory phase and its organizational setup are presented in Schmid et al. (2012b).

The focus of the research was on the one hand on the electricity sector - a sector for which technology options are readily available and where the discussion about mitigation has a longer lasting tradition in Germany. On the other hand, the transport sector was chosen as it is acknowledged that there are major difficulties in decarbonizing the transport sector (e.g. Luderer et al., 2012). Due to the limited scope of the project, a deliberation of technological mitigation options in the industrial and residential heat sector was not included in the participative process. However, the methodology outlined in Figure 1 and explained in the following can be transferred to more comprehensive scenario exercises in future research.

2.1. Participatory Scenario Definition

Scenarios are a linking tool that integrates qualitative narratives and quantitative formulations based on formal modeling (Nakicenovic et al., 2000). In order to define scenarios, i.e. formalize the link between the two elements, "parsimonious narratives" have been established in the IAM community. They consist of contextual information on anticipated key future developments and corresponding quantitative projections for boundary conditions (Kriegler et al., 2010) and intend to convey substantive meaning to a particular set of boundary conditions for IAMs.

Several parsimonious narratives for key future developments in the transport and electricity sector were developed in collaboration with CSO stakeholders during two dedicated stakeholder dialogues. One dialogue was conducted for each sector to allow for an in-depth discussion. The interdisciplinary research team pre-selected focal topics for each sector by striking a balance between technological mitigation options that are crucial from the point of view of the energy-economy model and developments that are likely to be subject to controversies regarding their social acceptance. The NGO partners conducted the selection of participants so as to cover the range of interest groups as good as possible given the limited scope of the project. The 11 and 13 participants in the transport and electricity sector stakeholder dialogues included representatives from environmental NGOs, industry and consumer associations, topic-related interest groups, urban planning, trade unions and industry. A detailed list of the represented organizations can be found in the Appendix. During the stakeholder dialogues, pre-selected mitigation options and associated key future developments were discussed with respect to direct and indirect implications and their perceived desirability. After each discussion, stimulated by an introductory question, a questionnaire elicited CSO stakeholders' positions for formal analysis.

The seven-point Likert-scale questionnaire (Likert, 1932) elicited judgments and preferences on possible future developments of key variables in the transport and electricity sector. For a number of possible developments, it asked to

indicate whether its realization is perceived as likely or not as well as desirable or not. Due to the small sample size, the data is not suited for econometric analysis. Instead, descriptive statistic measures of central tendency are employed. Mean, standard deviation and mode give an indication of whether the perceptions of likely and desirable developments diverge and whether there is a degree of agreement across stakeholders.

Along with the qualitative information obtained during the discussions as well as expert judgments from literature, the elicited data serves as a basis for generating sets of parsimonious narratives. Parsimonious narratives were developed for those mitigation options where stakeholders had an opinion and judgments on likely versus desirable developments diverged significantly or the desirability was particularly subject to dissent amongst stakeholders. This resulted in three scenarios. In order to keep the scenario definition tractable, a selection had to be made by the interdisciplinary research team and not all issues discussed during the stakeholder dialogues are actually differentiated in the scenarios. For those mitigation options which are not explicitly addressed by the scenario definition, the deployment decisions are endogenous to the model REMIND-D and boundary conditions are set equally for the scenarios according to expert judgments from literature. They can be consulted in the model documentation (Schmid et al., 2012a). It needs to be acknowledged that a mitigation scenario definition according to the criteria of likeliness, desirability with consent and desirability with dissent is not unique and influenced by the modeler's choice. Finally, the modeling team translates the parsimonious narratives into corresponding input parameter configurations for the model REMIND-D.

2.2. The Hybrid Energy-Economy Model REMIND-D

REMIND-D is a Ramsey-type growth model that integrates a detailed bottom-up energy system module coupled by a hard link (Bauer et al., 2008). It facilitates an integrated analysis of the long-term interplay between technological mitigation options in the different sectors of the German energy system as well as general macroeconomic dynamics. A detailed description of REMIND-D is

provided in Schmid et al. (2012a). REMIND-D builds on the structural equations of the state-of-the-art IAM REMIND-R (Leimbach et al., 2010) which are reported in Bauer et al. (2011). The objective of REMIND-D is to maximize welfare, i.e. the intertemporal sum of discounted logarithmic per capita consumption. Mitigation is enforced by means of a strict emission budget of 16 Gt CO_2 over the time horizon of the analysis, 2005-2050, resulting in roughly 85% emission reduction in 2050 relative to 1990. The budget approach is inspired by Meinshausen et al. (2009). When budgeting emissions, the model can choose annual emissions endogenously allowing for flexibility in the selection of mitigation options.

In REMIND-D, future scarcities of energy carriers and CO_2 emissions are anticipated through shadow prices, implying perfect foresight. Hence, REMIND-D features optimal annual mitigation effort and technology deployment as a model output. Available mitigation options fall into four categories: (i) Deploying alternative low-emission technologies, (ii) substituting final energy and energy service demands, (iii) improving energy efficiency and (iv) reducing demand. The latter is generally avoided by the model as demand reductions have a negative impact on GDP. Limitations of REMIND-D are mainly that it abstracts from secondary and final energy imports and possesses coarse technology resolution in the residential and commercial heat sector. Further, infrastructure investments are only represented for energy distribution technologies but not for transport system infrastructure like railroad tracks due to a lack of data.

The energy system module of REMIND-D is endowed with a variety of alternative technologies that it may deploy endogenously. Endogenous capacity deployment is subject to potential and resource constraints for renewable primary energies and fuel costs for fossil primary energies. The fossil primary energy carriers hard coal, natural gas and crude oil are imported at exogenous prices (Nitsch and Wenzl, 2009, price path B). Domestic lignite resources are represented by an extraction cost curve approach. Approximately 70 energy conversion technologies are considered explicitly, as are 20 distribution and 40 transport technologies. Conversion technologies produce the secondary en-

ergy carriers electricity, district heat, local heat, hydrogen, gas, petrol, diesel, kerosene and heating oil. Distribution technologies convert secondary energies into final energies as the industry and residential & commercial sector demands. Transport technologies provide energy services for passenger and freight relocation. Upon choice, the Carbon Capture and Sequestration (CCS) technology is available for the electrification and liquefaction of coal, lignite, gas and biomass from 2020 onwards. According to the decisions of the German Government, nuclear capacities are phased out until 2022. Domestic renewable energy potentials include lignocellulose, oily and sugar & starch biomass, manure, deep and near-surface geothermal, hydro, wind onshore, wind offshore and solar irradiation. Despite the time resolution in five-year steps, the model accounts for fluctuation of renewable electricity generation on short time scales explicitly via a residual load duration curve approach (Ueckerdt et al., 2011).

2.3. Participatory Scenario Evaluation

In the second round of stakeholder dialogues, the same CSO stakeholders as in the first round of dialogues evaluated the mitigation scenarios obtained with REMIND-D by discussing their plausibility and identifying where projected developments could raise concerns about social acceptance. The objective was to characterize critical socio-political implications of technological mitigation options. A better understanding of how goals of climate protection and energy security may conflict with those of an affordable energy supply for everybody and how these trade-offs can be tackled is essential for transforming Germany towards a low-carbon energy future.

3. Scenario Definition

As outlined in Section 2.1, the development of parsimonious narratives, consisting of contextual information on anticipated key future developments and corresponding quantitative projections for boundary conditions, is central to this scenario definition process. Three scenarios were defined according to the

criteria of likeliness, desirability with consent and desirability with dissent. The 'continuation' scenario enforces a set of parsimonious narratives in the transport and electricity sector that are deemed likely by CSO stakeholders. The 'paradigm shift' scenario reproduces a set of parsimonious narratives perceived as desirable by the majority of CSO stakeholders. A variant of the latter, the 'paradigm shift+' scenario, additionally allows for the deployment of several technological mitigation options which the stakeholders judged as undesirable or discussed controversially. Yet these technologies, e.g. CCS, are favored e.g. by the coal industry. Along the lines of the discussion questions raised during the stakeholder dialogues, the different parsimonious narratives are elaborated in the following.

Table 1: Selected results of the Likert-Scale questionnaire of the CSO stakeholder dialogue on the transport sector with 11 participants. All statements relate to the time horizon until 2050. 1 indicates disagreement, 4 neutrality and 7 agreement. STD = Standard Deviation, MS = Modal Split, MIT = Motorized Individual Transport, PT = Public Transport

	Likely			Desirable		
Future Development	Mean	STD	Mode	Mean	STD	Mode
Annual t-km truck increases	6.55	0.69	7	3.09	2.25	1
Shift t-km from road to rail	3.73	1.74	3	6.09	1.38	7
Decouple freight&GDP growth	4.09	1.3	3/4	5.90	1.87	7
MS MIT decreases to $\leq 50\%$	3.91	1.64	3/5	4.73	2.28	7
MS PT increases significantly	3.64	1.75	5	5.64	1.63	7
MS cycling&walking increases	4.55	2.07	2/7	5.64	1.97	7
Bioethanol $\geq 50\%$ share	3.33	1.55	2	3.33	2.33	1
Biodiesel $\geq 50\%$ share	3.33	1.79	3/5	3.33	2.33	1
Hydrogen dominant fuel	3.55	1.92	3	3.64	1.45	3

Is an increase of total annual freight mileage unavoidable? Historically, freight transportation and GDP growth rates correlated strongly, however, their

causal relationship is not straightforward (Feige, 2007). It is intertwined through the indirect influence of transport technologies on production and distribution structures as well as other aspects of industrial organization and fundamental economic variables, e.g. the degree of specialization, economies of scale, comparative advantage and diffusion of technological progress. As indicated in Table 1, decoupling freight and GDP growth rates by reducing annual truck mileage and shifting freight from road to rail is perceived as a desirable mitigation option by CSO stakeholders. Yet they anticipate annual ton-km (t-km) mileage with fossil-fuel-based trucks to increase continuously until 2050. This scenario is corroborated by expert judgments. Lenz et al. (2010), e.g., predict a dramatic increase in diesel truck mileage from 466 Bn t-km in 2005 to 787 Bn t-km in 2030, constituting a severe carbon lock-in. In the 'continuation' scenario, this trend is enforced by an exogenous linear increase of annual freight transport with trucks up to 787 Bn t-km in 2050 as a conservative estimate. However, the CSO stakeholders strongly advocated policy efforts directed at reducing total transport mileage and achieve a shift from road to rail. They claim that viable solutions exist but lack of political will impedes their implementation. Holzhey (2010) finds that a doubling of freight transport with rail in Germany until 2030 is technically possible even though concerted investments are required. Consequently, in the two 'paradigm shift' scenarios, it is assumed that freight transport and GDP growth can be decoupled in the future.

Is multi-modality a viable option for decarbonizing the passenger transport sector? The modal split in the passenger transport sector is heavily biased towards motorized individual transport (MIT) with cars accounting for roughly 80% of travelled person-km (p-km) annually (BMVBS, 2008). CSO stakeholders expect MIT to remain the dominant mode of transportation in the future. Hence, the 'continuation' scenario is bound to a share of 80% MIT in modal split annually. However, CSO stakeholders perceive a structural change in the modal split as a desirable future development, seeing some potential for public transport (PT) and also non-motorized short distance transport to increase, e.g. by means of a fast bicycle lane network. CSO stakeholders particularly

stress the importance of increasing infrastructure investments for PT to enable multi-modality transport patterns, supporting the proposals of the European Commission's white paper on transport (EC, 2011). By prescribing an increase in the share of PT in the modal split for both short and long distance passenger transport, these developments are reproduced in the two 'paradigm shift' scenarios.

Which alternative low-carbon fuels ought to be dominant in the future? Instead of a shift in the mode of transportation, less carbon-intensive fuels for conventional vehicles are another technological mitigation option. Biodiesel can be produced from bio-oils and bioethanol from sugar and starch biomass; in the future, second generation biofuels from lignocellulose will possibly become available (e.g. Schulz et al., 2007). Other low carbon technologies for fuel production include the liquefaction of hard coal or lignite in combination with CCS and a shift towards hydrogen. CSO stakeholders are controversial about the desirability of first-generation biofuels and doubt that second-generation biofuel technologies will be available in large scale. Likewise, they doubted the technological feasibility of a hydrogen future (e.g. Fischedick et al., 2005), exploiting overproduction of REG capacities via electrolysis. Since the desirability of these technological options was contested, they are available to the model only in the 'paradigm shift+' scenario.

Are landscape externalities of renewable electricity generation (REG) capacities and transmission lines problematic and what are potential remedies? A concomitant effect of large-scale deployment of REG and transmission line (TL) capacities is that they technologize the landscape. This landscape externality was in fact considered problematic with regard to social acceptance. Especially biogas electrification, accompanied by large corn monocultures, were judged as unacceptable, see Table 2. CSO stakeholders expect that substantial TL extensions, necessary to distribute and balance fluctuating REG, are potentially impeded due to local resistance. However, they find it desirable that such local oppositions are resolved and encourage that REG technologies, with the exception of biogas electrification, constitute a very large share of the electricity mix

in the future. Possible remedies for fostering social acceptance towards REG and TL capacities include procedural justice and increased participation and ownership by the local population (Musall and Kuik, 2011; Zoellner et al., 2008). To represent the effect of a certain degree of social refusal towards large-scale REG and transmission line deployment in REMIND-D, the REG potentials in the 'continuation' scenario are lower than in both 'paradigm shift' scenarios.

Table 2: Selected results of the Likert-Scale questionnaire of the CSO stakeholder dialogue on the electricity sector with 13 participants. All statements relate to the time horizon until 2050. 1 indicates disagreement, 4 neutrality and 7 agreement. STD = Standard Deviation, TL = Transmission Lines, IND = Industry, HHS = Households, PP = Power Plant, CCS = Carbon Capture and Sequestration

	Likely			Desirable		
Future Development	Mean	STD	Mode	Mean	STD	Mode
Local resistance impedes TL	3.57	1.40	2/3/5	1.46	0.66	1
Deploy heavily wind offshore	5.64	1.34	5	4.92	1.89	7
Deploy heavily biogas plants	4.21	1.25	5	3	1.63	2
Elec. demand IND decreases	4.71	1.86	6	4.77	1.94	4/6/7
Elec. demand HHS decreases	4.07	1.90	3	5.07	2.10	7
Rebound effect compensates	5.14	1.35	5	2.92	1.55	1/3/4
Increase Gas PP next decade	5.43	1.16	5	5.54	2.03	6
Decommission existing Coal PP	4.36	1.55	5	5.23	2.24	7
Large scale availability CCS	3.54	1.94	1/4	3.58	2.35	1

Which energy efficiency growth rate is feasible and what is the role of the rebound effect? It is widely agreed that energy efficiency improvements are an important mitigation option in Germany especially for the electricity sector. Yet CSO stakeholders expect electricity demand to remain stable or increase in the future, despite judging high efficiency growth rates as a desirable development. Institutional barriers to exploiting technical energy efficiency potentials are sub-

stantial, e.g. lack and asymmetry of information, principal-agent problems, split incentives, hidden costs or bounded rationality (Gillingham et al., 2004). Also, the rebound effect is likely to prove itself as a real obstacle. It postulates that energy efficiency increases make individual energy services cheaper, leading to an increase in their consumption or the consumption of other carbon-intensive energy services (e.g. Sorrell et al., 2009). In order to translate these judgments, efficiency growth rates of the final energy demand perpetuate historical trends in the 'continuation scenario' averaging 0.5 % annually. The two 'paradigm shift' scenarios assume significant improvements and the exogenous efficiency growth rates of final energy demand amount to an average of 2.3 % annually.

Which thermal electricity generation capacities are acceptable in the next decades? Due to the phase-out of nuclear until 2022, these generation capacities need to be replaced within the next decade. CSO stakeholders oppose the built-up of new CO_2 emission-intensive coal power plants. Instead, they consider it both likely and desirable to deploy gas power plants which are not only less CO_2-intensive but are also better capable of balancing fluctuating REG (dena, 2010). 33% of all energy-related German CO_2 emissions in 2009 were incurred by lignite and hard coal power plants. The option of decommissioning them before the end of their techno-economic lifetime and replacing them with REG capacities, albeit hardly discussed, constitutes an effective mitigation option. Even though CSO stakeholders judged this option as desirable, they consider it as moderately realistic. To simulate a carbon lock-in from persistent coal electrification, existing hard coal and lignite power plants are subject to a must-run constraint in the 'continuation' scenario. This must-run constraint implies that the coal power plants may not be put out of service before the end of their technical lifetime. A large-scale deployment of the CCS technology was judged as neither particularly likely nor desirable and is hence available to the model only in the 'paradigm shift+' scenario from 2025 onwards.

Table 3 summarizes the model constraints defining the three scenarios. As already mentioned, the deployment of all mitigation options not mentioned in Table 3 is left endogenous to the model REMIND-D. Given that all scenarios

Table 3: Summary overview of the model constraints that define the three scenarios, resulting from the participatory process. FT = Freight Transport, PT = Public Transport, MS = Modal Split, REG = Renewable Electricity Generation, PP = Power Plant, CCS = Carbon Capture and Sequestration

Model Constraint	Continuation	Paradigm Shift	Paradigm Shift+
Decoupling FT&GDP	no	yes	yes
PT share in MS	constant	increase	increase
REG potential	medium	high	high
Energy efficiency	medium	high	high
Decommission Coal PP	no	yes	yes
CCS by 2025	no	no	yes
Biofuel potential	low	low	high

are required to achieve ambitious mitigation, the scenario definition indicates that the 'continuation' scenario represents the most restrictive setup, especially because the freight transport and electricity sector are bound to certain CO_2 emissions by definition. Thus, the scenario constitutes a counterfactual exercise illustrating what would need to happen in the other sectors for achieving ambitious mitigation if these likely trends persisted and energy efficiency and REG potentials are not fully exploitable due to institutional barriers and societal resistance. On the contrary, the two 'paradigm shift' scenarios correspond to a world in which fundamental policy changes are successfully implemented. Here, tremendous progress is achieved in energy efficiency and REG deployment and carbon lock-in in terms of committed CO_2 emissions is avoided.

4. Scenario Results

The model REMIND-D finds an optimal solution for each of the scenario configurations, despite the strict emission budget of 16 Gt CO_2. Before going through the results, it needs to be highlighted once more that they are derived

under the assumption of perfect foresight and constitute deterministic first-best solutions rather than forecasts. This is especially relevant to the counterfactual 'continuation' scenario which is forced to achieve ambitious mitigation despite restrictive boundary conditions. Notwithstanding these abstractions, the scenario results yield valuable insights into stylized trends and interrelations across sectors under different scenario configurations. The following presents for each scenario the CO_2 emissions, trends in the transport and electricity sector as well as mitigation costs.

4.1. CO_2 Emissions by Sector

Mitigation shares of the three sectors transport, electricity and heat structurally differ across scenarios as illustrated in Figure 2. CO_2 emission reductions between 2005 and 2015 are similar in all scenarios – a fast decrease of emissions of 29-32% in the electricity sector, 29-32% in the industrial, residential and commercial heat sectors and 4-9% reduction in the transport sector. From 2015 onwards, there are structural differences between the developments in the 'continuation' and both 'paradigm shift' scenarios. The speed of emission reduction in the electricity sector stagnates in the 'continuation' scenario due to the must-run constraint for the existing lignite and hard coal power plants. Additional committed emissions in the 'continuation' scenario originate in the prescribed increase in freight transport with trucks. The total carbon lock-in over the time horizon of analysis, 2005-2050, amounts to 6.15 Gt CO_2 from coal electrification and 2.67 Gt CO_2 from freight transport. In sum, these 8.8 Gt CO_2 deplete 55% of the total emission budget. Consequently, the heat sector needs to deliver a substantially higher mitigation effort in the 'continuation' scenario than in the two 'paradigm shift' scenarios in order to meet the total CO_2 emission budget.

In the two 'paradigm shift' scenarios, the electricity sector decreases CO_2 emissions much faster, delivering a reduction of 80% between 2005 and 2020. Therefore, more CO_2 emissions can be incurred in the heat sector providing process heat for industry and residential heating. This structural effect is even more pronounced in the 'paradigm shift+' scenario; here, the availability of new

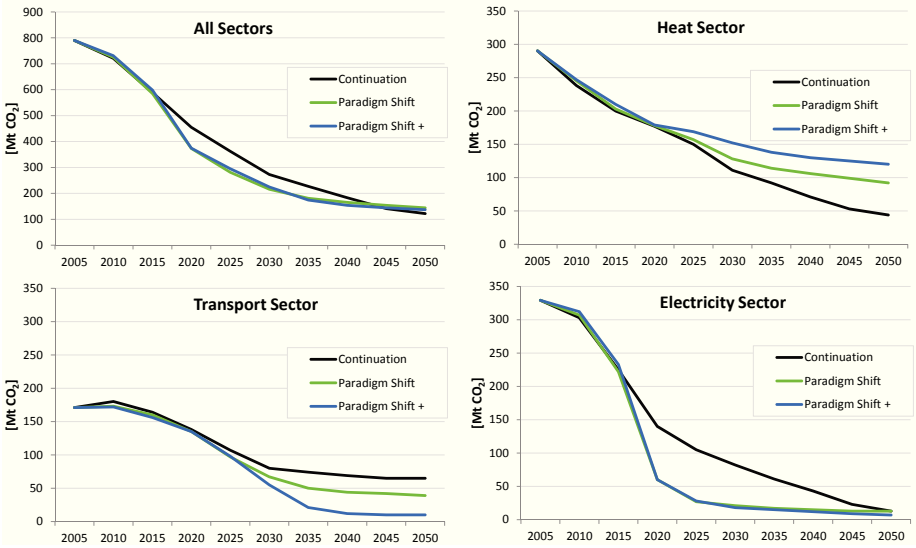

Figure 2: Annual CO_2 emissions from energy in Germany for 2005-2050 in Mt per year, by scenario and sector. These model results are obtained with REMIND-D

low-carbon technologies leads to an almost complete decarbonization of the freight and electricity sectors by 2035. These findings illustrate the advantage of an integrated approach to mitigation modeling allowing for an analysis of the interplay between different sectors.

4.2. Transport Sector

Until 2050, total CO_2 emissions within the transport sector decrease by 47% in the 'continuation', 73% in the 'paradigm shift' and 93% in the 'paradigm shift+' scenario versus 2005. The majority of annual reductions are achieved during the next two decades, yet the drivers differ across the three scenarios. Clear structural breaks emerge in both modal splits in the two 'paradigm shift' scenarios.

Aggregate trends in the freight sector for each scenario are illustrated in Figure 3. The y-axis measures annual freight transport mileage in Bn t-km per year, whereas the x-axis displays the three sectors for each scenario. Time is indicated by color coding. First, Figure 3 visualizes the structure of the sectoral

relationships in one scenario, highlighted by the connecting lines in the years 2005, 2020 and 2050. Second, the sectoral trends over time can be compared across scenarios. And third, it emphasizes the speed of transformation: The larger the white areas are within a bar, the faster is the CO_2 emission reduction between two time steps.

In all scenarios, freight transport by inland water navigation remains constant due to its limited potential. In the 'continuation' scenario, freight train capacities also remain at today's levels, however, freight transport with trucks increases continuously due to the scenario assumption of coupled GDP and freight transport growth rates. In consequence, the freight sector's annual emissions remain constant at 60-70 Mt CO_2 as the availability of alternative low-emission fuels is limited in this scenario. These committed emissions are avoided in both 'paradigm shift' scenarios. Here, the decoupling indicator (t-km/GDP) does not increase by 20% from 2005 to 2050 but decreases by 20% and 10%, respectively. Apart from keeping freight transport mileage constant at today's level, through a restructuring the economic system towards less transport-intensive value chains, mitigation is enabled by massive rail infrastructure expansions allowing for train mileage to tripe until 2030. In the 'paradigm shift+' scenario, the truck mileage remains at higher levels than in the 'paradigm shift' scenario due to the availability of alternative low emission fuel technologies, e.g. second generation biofuels and liquefaction of lignite in combination with the CCS technology.

As regards the passenger sector, annual per capita mileage decreases from 13,000 km in 2005 to 11,000 km in the year 2050 in both 'paradigm shift' scenarios; the parsimonious narrative foresees that one part of the difference will be substituted by non-motorized traffic, i.e. cycling and walking. In the 'continuation' scenario, however, the per capita p-km are forced to decrease down to 9000 p-km in 2050 due to mitigation pressure induced by the carbon lock-in in the freight and electricity sector.

The total annual p-km by transport mode for each scenario are illustrated in Figure 4. Here, the structural change in both 'paradigm shift' scenarios

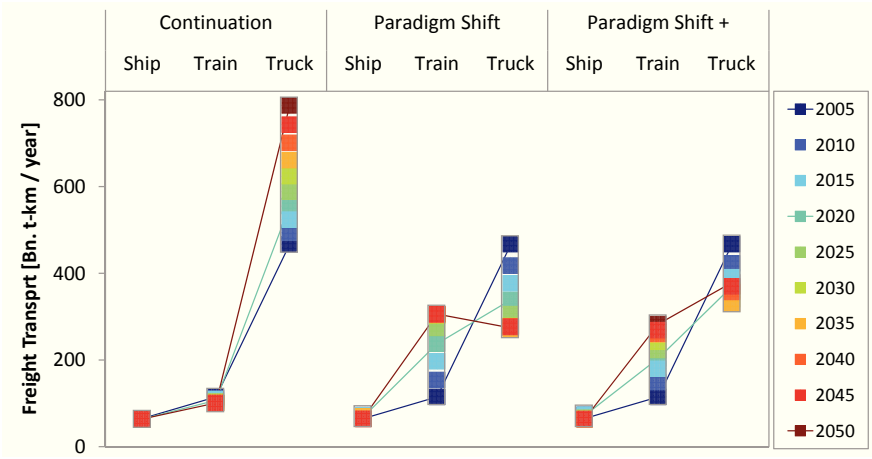

Figure 3: Annual freight transport mileage for 2005-2050 in Bn ton-km (t-km) per year, by scenario and mode. These model results are obtained with REMIND-D

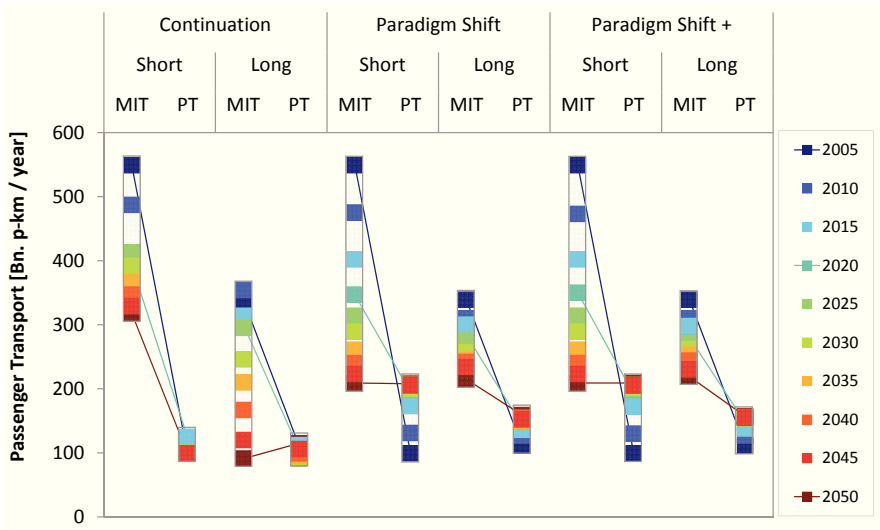

Figure 4: Annual passenger transport mileage for 2005-2050 in Bn passenger-km (p-km) per year, by scenario and mode. These model results are obtained with REMIND-D. MIT = Motorized Individual Transport, PT = Public Transport

becomes evident: MIT decreases at a decreasing rate until 2050 and PT steadily increases until 2020, remaining constant thereafter. Hybrid buses, electrified light rail and regional trains deliver additional short distance PT. Together, they account for roughly 50% of the modal split of short distance transport in 2050. Incremental long distance PT will be delivered with electric trains. In all scenarios, anticipated carbon budget restrictions and implicit carbon pricing make conventionally fuelled cars too expensive to operate so they are phased out entirely until 2030. Diesel cars, predominantly suitable for long distance driving, are first substituted by diesel hybrids and then by hybrid gas cars in all scenarios. Petrol cars are replaced with hybrid-plug in gasoline cars which are electric cars with a petrol-fuelled rage extender. In the 'paradigm shift+' scenario, they are partly replaced with hydrogen hybrid cars as hydrogen is produced from lignocelluloses with CCS here, with the ability to extract CO_2 from the atmosphere and producing de-facto "negative" CO_2 emissions. In all scenarios, there is a trend to gradually electrify the transport sector with the total demand of electricity for transport increasing by several orders of magnitude until 2050, yet never exceeding 15% of the total electricity production.

4.3. Electricity Sector

The aggregated technology mix of the electricity sector for the three scenarios is illustrated in Figure 5. In the two 'paradigm shift' scenarios, where the model is given the option to decommission existing hard coal and lignite power plants from 2015 onwards, these capacities are shut down by 2020. They are temporarily replaced by gas turbines, about 25 GW capacity are built between 2015 and 2020. Once enough REG capacity is installed, the gas turbines go out of service again in both 'paradigm shift' scenarios by 2030. In the 'continuation' scenario, there is no such temporary increase in gas capacities as existing coal and lignite power plants continue to produce electricity. In all scenarios, REG is rapidly expanded and doubling over the next five years.

From 2020 onwards, the installed REG capacities stagnate in the 'continuation' scenario. This is due to the moderate potential in the scenario definition,

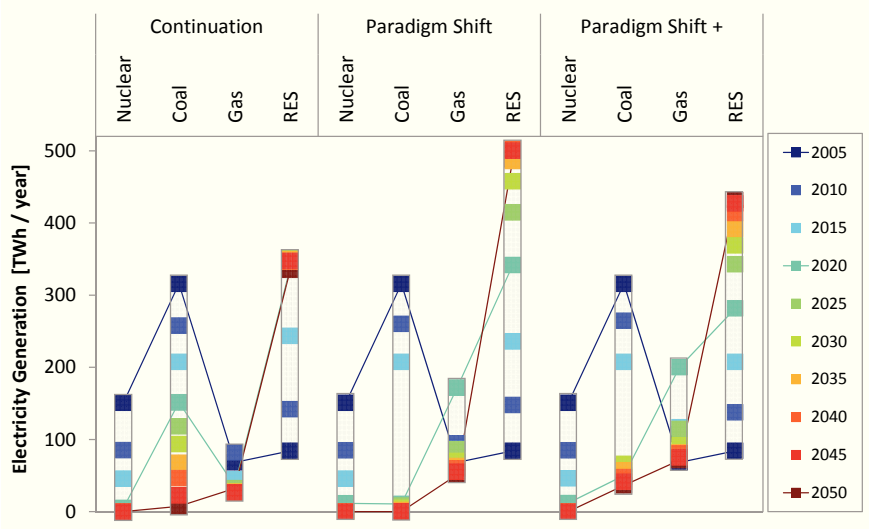

Figure 5: Annual electricity generation for 2005-2050 in MWh per year, by scenario and aggregated technologies. These model results are obtained with REMIND-D

motivated by a restrictive public attitude that constrains the incremental deployment of RE capacities and transmission lines. Total electricity production is forced to decrease from 620 TWh in 2005 to 375 TWh in 2050. Because of the carbon lock-in from freight transport and coal electrification, the model cannot afford to allocate more CO_2 from the emission budget to the electricity sector for covering gas turbines. These could provide more balancing capacities so solar potentials could be fully exploited which is not the case in the 'continuation' scenario. Instead, REMIND-D opts for the least attractive mitigation option of imposing electricity demand reductions in all sectors, including industry. A consequence of this is a reduction in GDP growth.

In both 'paradigm shift' scenarios, REG capacities continuously expand, especially offshore wind, and total electricity production stabilizes between 530 and 560 MWh. The slightly reduced demand is due to high efficiency growth rates. In 2050, onshore wind capacities reach a maximum of 100 GW in both 'paradigm shift' scenarios. Offshore capacities reach 150 GW in the 'paradigm shift' scenario and 180 GW in the 'paradigm shift+' scenario. Geothermal elec-

tricity production also plays a vital role in all scenarios with 20-35 GW installed capacity. REMIND-D installs 110 GW of solar photovoltaic in the 'continuation' scenario by 2050. In the 'paradigm shift' scenarios, other less expensive technologies, e.g. wind onshore and offshore, provide sufficient electricity generation potential and solar photovoltaic plays only a minor role. Biomass electrification plays a subordinate role in all scenarios as REMIND-D prefers to use all available biomass for fuel production. In the 'paradigm shift+' scenario, 14 GW of lignite power plants with the oxyfuel CCS technology are installed as well as 25 GW of natural gas combined cycle plants with CCS. When compared to the 'paradigm shift' scenarios, these capacities somewhat reduce the need for REG.

4.4. Mitigation Costs

Comparing the results of two scenarios that differ with respect to the emission constraint only allows for determining the differential effects of mitigation enforcement. One measure of economic mitigation costs is the cumulative difference in discounted GDP losses (referred to as cumulative GDP losses hereafter) between two scenario runs that have the same restrictions, except for the size of the CO_2 emission budget.

Figure 6 illustrates how cumulative GDP losses between scenarios diverge with increasingly strict carbon budgets. For ease of interpretation, the x-axis displays the respective % of CO_2 emission reduction achieved in 2050 relative to 1990. Macroeconomic mitigation costs in terms of cumulative GDP losses for the 'continuation', 'paradigm shift' and 'paradigm shift+' scenario amount to 3.5%, 1.4% and 0.8% between 2005 and 2050. The respective reference case with a larger carbon budget leads to moderate 40-45% CO_2 emission reduction in 2050 relative to 1990. For moderate mitigation targets up to 65% CO_2 emission reduction in 2050, GDP losses remain below 0.5% in all scenarios. Mitigation costs in this order of magnitude are also found by global IAM analyses (e.g. Edenhofer et al., 2010; Luderer et al., 2012). However, for more ambitious targets, the mitigation costs in the 'continuation' scenario increase relatively faster than in the two 'paradigm shift' scenarios. This divergence is induced

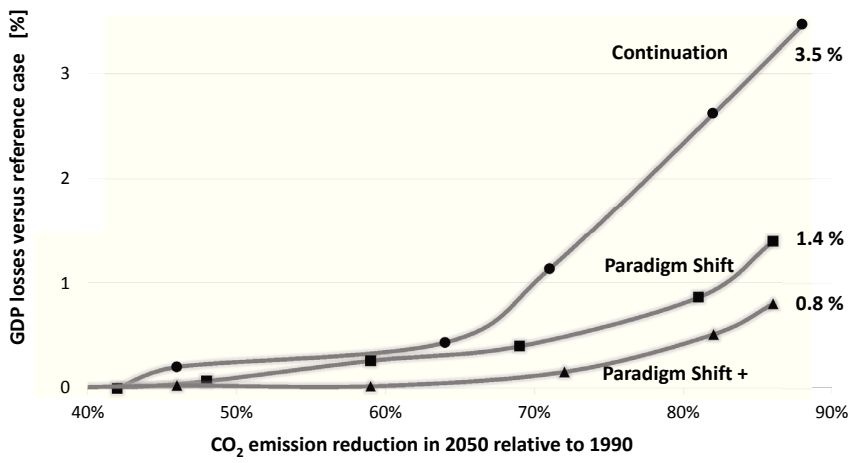

Figure 6: Mitigation cost curve for the three scenarios, in terms of cumulative discounted GDP losses compared to a respective reference scenario with 40-45% CO_2 emission reduction in 2050. These model results are obtained with REMIND-D.

through the differences in scenario assumptions.

The main drivers for increasing GDP losses in the 'continuation' scenario are moderate efficiency growth rates and endogenously enforced demand reductions because of the aforementioned carbon lock-in in the freight and electricity sector. GDP losses remain significantly lower for all mitigation targets in the 'paradigm shift' scenario. Higher efficiency growth rates in all sectors of the economy, larger REG potential and the option to avoid the carbon lock-in are responsible for this. In terms of the underlying parsimonious narratives, the results indicate that ambitious mitigation in Germany can be achieved at relatively lower costs if structural changes in modal splits of the freight and passenger transportation sector and a fast decarbonization of the electricity sector are pursued.

Mitigation costs in the 'paradigm shift+' scenario remain even lower for all levels of mitigation ambition. This is due to additionally available technological mitigation options in the form of CCS and larger biofuel potentials and in line with findings in other scenario exercises (e.g. Edenhofer et al., 2010; Luderer et al., 2012). Yet the incremental effect is not as decisive as moving from the

'continuation' to the 'paradigm shift' scenario.

5. Scenario Evaluation

CSO stakeholders perceive three projected developments in the 'continuation' scenario as implausible mainly due to socio-political implications that conflict with objectives in other policy arenas. First, the model results indicate a strong decrease of motorized individual transport that is not compensated for by more public transport mileage. Massive state intervention would be necessary to induce behavioral changes of such magnitude, e.g. through carbon pricing policies entailing prohibitively high transport costs. In such a world, individual mobility would become a luxury good. The CSO stakeholders assess that such policies will lack social acceptance and strongly emphasize the value of individual mobility in modern societies. Second, the required electricity and heat demand reductions are considered as politically not enforceable in reality. To induce such a development, again, rigorous carbon pricing policies would be required which would increase the price of electricity and heating substantially. Several stakeholders pointed out the dangers of energy poverty if any such mitigation policy is not accompanied by effective redistribution schemes. Third, the CSO stakeholders doubt that the projected CO_2 emission reductions and efficiency improvements in the heat sector can be realized, seeing institutional barriers as for example the well-known landlord-tenant conflict of responsibility.

In sum, these critical socio-political implications motivated the CSO stakeholders to assess the 'continuation' scenario as highly undesirable, despite the fact that it reaches the required mitigation target. Yet they reconfirmed the likeliness of its projected developments in the freight transport and electricity sector, leading to a lock-in into current behavior and carbon-intensive infrastructure. In consequence, they conclude that, if the carbon lock-in becomes reality, ambitious mitigation targets will likely be out of reach.

The 'paradigm shift' scenarios see the carbon lock-in resolved. CSO stakeholders largely corroborate the desirability of its proposed developments, espe-

cially the fast increase in renewable electricity generation. However, they point out that several model projections appear unrealistic such as the near-term decommissioning of coal power plants, the rapid shift from road to rail in freight transport or the widespread electrification of private transport until 2030 and the simultaneous shift to public transport. They doubt that it is possible to establish the necessary collective political will for enforcing policies that lead to such technology deployment.

Several concerns were articulated for policies that aim at inducing the structural breaks from historical trends inherent to the 'paradigm shift' scenario: The quality of public transport services needs to increase significantly, both in urban environments and in rural areas. Inter alia, this would require a redirection of infrastructure investments from road to rail, an issue considered long overdue by the CSO stakeholders. Furthermore, the projected rapid decommissioning of existing coal power plants may entail increasing regional unemployment rates in Germany's structurally weak lignite mining areas. Finally, a fast deployment of renewable electricity generation and transmission line capacities requires high procedural justice throughout the planning and installation process, including institutionalized possibilities for local communities to participate, also financially. CSO stakeholders preferred the 'paradigm shift' scenario over the 'paradigm shift+' scenario as they predict substantial public protest against the large-scale deployment of CCS infrastructure and biofuel production. They argue that the incremental effect on decreasing mitigation costs may not outweigh the direct and indirect costs of public protest.

6. Summary and Conclusion

This paper presents three model-based mitigation scenarios for Germany that achieve 85% CO_2 emission reduction in 2050 relative to 1990. These scenarios were defined and evaluated in a participatory process with CSO stakeholders. During separate dialogues, their preferences on future developments related to mitigation in the transport and electricity sector were discussed and

elicited. Along with findings from literature, the input from the CSO stakeholders built the basis to generate parsimonious narratives on future developments of key variables in the transport and electricity sector according to the criteria of likeliness, desirability with consent and desirability with dissent.

The 'continuation' scenario is characterized by enforcing a set of developments that are deemed highly likely by all participants. These include the dominance of motorized individual transport, unabated coal electrification, moderate energy efficiency growth rates, local resistance against windmills and transmission lines as well as the continuation of coupled freight transport and GDP growth rates. Coal electrification and fossil-fuel-based freight transport mileage induce 8.8 Gt CO_2 of committed emissions. This carbon lock-in accounts for 55% of the total CO_2 emission budget over the time horizon of analysis from 2005 to 2050. As a consequence, non-technical mitigation options slowing down economic growth are exploited by REMIND-D for meeting the CO_2 budget constraint. These include significant energy service demand reductions in passenger transportation as well as final energy demand reductions for electricity and the provision of heat. Additionally bound to moderate energy efficiency improvements, the 'continuation' scenario exhibits mitigation costs of 3.5 % cumulative GDP losses over the period 2005-2050 as compared to a reference case that achieves 40% CO_2 emission reduction in 2050 relative to 1990. Stakeholders judged the results of this counterfactual scenario as highly problematic from a socio-political point of view and conclude that under carbon lock-in, ambitious mitigation will likely be out of reach.

The two 'paradigm shift' scenarios reproduce future developments judged as desirable by participating stakeholders. These include a decrease in total freight transport mileage, a shift in the modal split of freight transport sector from road to rail, a substantial increase of public and non-motorized transport in the modal split of passenger transportation, a widespread electrification of private transport by 2030, a phase-out of conventional coal electrification until 2020, a rapid and large-scale deployment of renewable electricity generation and transmission line capacities as well as a fourfold increase in energy efficiency growth rates.

REMIND-D immediately exploits these mitigation options whereby mitigation costs decrease by more than half when compared to the 'continuation' scenario, with 1.4% of cumulative GDP losses. Yet the necessary fundamental policy changes for such a scenario are put into question by stakeholders as they doubt that sufficient collective political will can be established. The 'paradigm shift+' scenario which additionally allows for the controverial use of CCS and large-scale biofuel production achieves even lower mitigation costs of 0.8%. However, CSO stakeholders remain skeptical whether these technologies are feasible in large scale, particularly due to social refusal.

Overall, the deliberative elements in this participatory mitigation scenario exercise have demonstrated that the transformation towards a low-carbon energy system constitute as much a societal effort as an engineer's project. Socio-political implications of technological mitigation options are abundant and would indeed have an impact on the society as a whole. It is questionable, however, if the institutional aspects to the use of energy services can be adapted as rapidly as suggested by the optimal scenarios derived under the assumption of perfect foresight. This corroborates the thoughts of Unruh (2000) who suggests that energy model results are biased due to abstracting from technological evolution and institutions. He argues that sectors of the energy systems cannot be comprehended as discrete technological artifacts but rather as complex systems of technologies embedded in a powerful conditioning social context of public and private institutions.

However, the direct implementation of social context and institutions into numerical energy system models appears impossible due to a lack of theoretical concepts and unobservability of data. In order to attach contextual meaning to parameters in available energy system models, the use of narratives, as explored in this paper, proves to be a promising avenue. Pursuing a participatory approach to developing mitigation scenarios results in a much stronger focus on the process of scenario definition and evaluation and allows for the explicit attachment of normative consideration to modeling results. As a form of scientific policy advice, such scenarios deal with value judgments openly and do not

attempt to hide them behind seemingly factual or technical statements.

Even though the limited scope of this research impedes inferential conclusions on the German energy transition as a whole, it has demonstrated that the technological solutions to the mitigation problem proposed by the model results give rise to significant societal and political implications that deem at least as challenging as the mere engineering aspects of innovative technologies. These insights underline the importance of comprehending mitigation of energy-related CO_2 emissions as a socio-technical transition embedded in a political context. Thus, in future mitigation scenario exercises the questions of how to govern the transition and which kinds of policy instruments are suitable for enabling the transition should be treated more explicitly. If this participatory research could be repeated under these considerations and at larger scope and scale, emerging mitigation scenarios potentially enjoyed a higher level of ownership and acceptance amongst societal and political actors and ideally contributed to shared vision-building.

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Appendix

List of organizations participating in the stakeholder dialogues on the transport sector: World Wide Fund For Nature (WWF), Germanwatch e.V., FUSS e.V. - Fachverband Fußverkehr Deutschland, Verkehrsclub Deutschland e.V, Allgemeiner Deutscher Automobil-Club e.V. (ADAC), Allgemeiner Deutscher Fahrrad-Club e.V. (ADFC), Verband Deutscher Verkehrsunternehmen e.V. (VDV),

Allianz pro Schiene e.V., Region Hannover Verkehrsentwicklung und Verkehrsmanagement, Daimler AG, Verband der deutschen Biokrafstoffindustrie e.V.

List of organizations participating in the stakeholder dialogues on the electricity sector: Naturschutzbund Deutschland e.V. (NABU), klima-allianz deutschland, e5 - European Business Council for Sustainable Energy, World Wide Fund For Nature (WWF), Germanwatch e.V., Brot für die Welt (Diakonisches Werk der Evangelischen Kirche in Deutschland e.V.), Bundesverband Erneuerbare Energie e.V. (BEE), Bundesverband Verbraucherzentralen, TenneT TSO GmbH, 50Hz Transmission GmbH, LichtBlick AG, RWE AG, Industriegewerkschaft Bergbau, Chemie, Energie (IG BCE).

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Chapter 5

Renewable Electricity Generation in Germany: A Meta-Analysis of Mitigation Scenarios*

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*submitted to *Energy Policy*

Renewable Electricity Generation in Germany: A Meta-Analysis of Mitigation Scenarios

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Abstract

This paper investigates a number of strategic questions relevant for the long-term transformation of the German electricity sector towards high shares of electricity generation from renewable energy sources (RES-E), by means of a meta-analysis of ten model-based mitigation scenarios from six recent publications. The scenarios group into three different energy strategies that exploit the basic options of domestic RES-E production, energy efficiency improvements and RES-E imports to a different extent. We identify several behavioral, institutional and engineering barriers to implementation that apply to all suggested energy strategies. Furthermore, we analyze RES-E technology choice and RES-E capacity investment requirements. The scenario projections indicate that wind offshore and onshore are the most important technologies. Yet, the studies rarely address the systemic effects of high shares of fluctuating RES-E explicitly, resulting in doubtfully optimistic techno-economic assumptions. Upon investigating the reasons why scenario projections diverge, it turns out that they are in many cases based on expert judgments rather than resulting from numerical modeling. These involve normative judgments and need to be made more explicit in future research. Also, scenario assumptions need to be motivated and elaborated on more explicitly since they have a decisive impact on the analytical quality of scenario projections.

Keywords: Energy strategy, Institutional barriers to implementation, Energy System Modeling

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1. Introduction

Having accomplished 20% CO_2 emission reduction in 2011 relative to 1990, the German Government aims at an ambitious long-term target of 80-95% in 2050 (2010). In order to achieve such deep emission reductions, the predominantly fossil fuel based German energy system will have to undergo a substantial transformation. By providing consistent projections of technology deployment pathways, model-based mitigation scenarios are an important source of information on how this transition towards a low-carbon Germany can be realized. Several mitigation scenarios that are consistent with the Government's mitigation targets exist in the literature, each relying on different objective functions, quantitative models and choices of uncertain input assumptions. Thus, it is of particular interest to understand how available mitigation scenarios compare: Is it possible to identify energy strategies that are common across scenarios? Are there robust – or controversial – findings? What are reasons and drivers for similarities and differences across mitigation scenarios?

The scope of this meta-analysis is confined to the electricity sector which was responsible for 45% of energy related CO_2 emissions in Germany in 2011 (BMWi, 2012). In the same year, electricity generation from renewable energy sources (RES-E) already contributed as much as 20% to domestic electricity provision (BMU, 2012b), resulting from a globally unprecedented growth in RES-E capacity deployment over the past two decades. This development was triggered by a feed-in tariff system installed with the Grid Feed-In Law in 1991 and accelerated by its successor the Renewable Energy Sources Act from the year 2000. In the last amendment of the Renewable Energy Sources Act in 2011 §1(2) was changed from aiming at a "continuous increase in the share of RES-E in electricity provision" after 2020 to defining minimum targets of 50%, 65% and 80% in 2030, 2040 and 2050, respectively. Hence, the German Government strives to transition towards the "age of renewables" within the next decades (Federal Government, 2010).

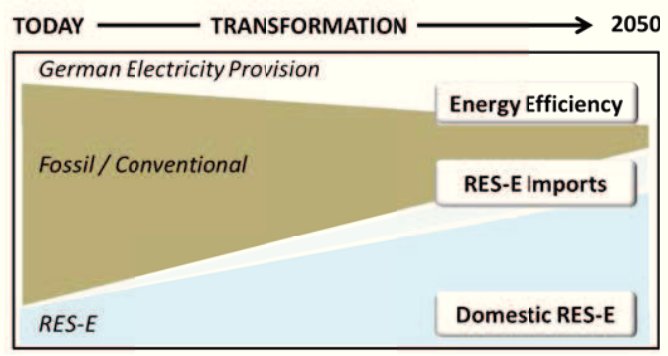

Figure 1. Schematic overview of strategic options for the long-term transformation of the German electricity sector.
RES-E = electricity generation from renewable energy sources

Against this background the German policy maker is confronted with a number of strategic questions relevant for the long-term transformation of the German electricity sector towards a high share of RES-E. A first set of questions relates to the basic strategic options available for the transformation, compare Figure 1: Which level of domestic RES-E production is required? What is the role of energy efficiency and RES-E imports in this context? A highly relevant question is which RES-E technologies are of major importance, e.g. for the further development of the German feed-in tariff system. And finally, how much needs to be invested in RES-E capacities? In Section 2.1, this paper investigates answers to these energy strategy relevant questions by means of a meta-analysis of scenario projections of ten mitigation scenarios drawn from six recent publications, see Table 1.

Table 1. Overview of mitigation scenarios considered in this analysis. Selection criteria for the scenarios included that they are (i) based on quantitative modeling (ii) consistent with the Government's long-term mitigation target and (iii) analyzing the time horizon until 2050

Publication	Scenario(s)
(WWF, 2009)	Innovation scenario **[Inn]** and its variant allowing for the Carbon Capture and Sequestration (CCS) technology **[Inn_CCS]**
(EWI/GWS/Prognos, 2010)	**[A1]**, the scenario with the lowest extension of the nuclear-phase out of 4 years (until 2026)
(DLR/IWES/IFNE, 2010)	Scenarios **[A]** and **[B-100%-S/H2],** which assumes a higher share (33% vs. 66%) of electro mobility in 2050's motorized individual transport mileage
(DLR/IWES/IFNE, 2012)	Updated version of scenario **[A]**, assumes 50% share of electro mobility
(Schmid and Knopf, 2012)	Paradigm shift scenario **[PS]** and its variant **[PS+]**, which additionally allows for CCS and large-scale biofuel production
(SRU, 2011)	Scenarios **[2.1.a]** and **[2.1.b]**, which differ in assumptions on electricity demand in 2050 (500 vs. 700 TWh)

It turns out that the scenarios can be grouped into three distinct energy strategies which exploit the strategic options of increasing domestic RES-E production, decreasing electricity demand and increasing RES-E imports to different extents. Section 2.2 identifies several behavioral, institutional and engineering barriers to implementation that apply to all identified energy strategies. For developing a robust energy strategy for the German electricity sector it is of particular interest to understand why the scenario projections are so different. In order to elucidate reasons and drivers for diverging scenario projections Section 3 investigates the individual modeling methodologies and compares underlying techno-economic assumptions. Section 4 summarizes and concludes.

2. From Scenarios to Strategies

Mitigation scenarios derived with quantitative models can be seen as complex thought experiments of the semantic form "if → then". The "if" is resembled by the set of input assumptions; the arrow represents the quantitative model which yields projections of energy system developments representing the "then". This part of the meta-analysis considers only the "then" dimension for investigating the aforementioned strategy-relevant questions on the long-term transformation of the German electricity sector towards high shares of RES-E. Doing so implies a strict model democracy in the sense of valuing results equally regardless of the quality of input assumption and analytical merits (cp. Knutti, 2010).

2.1 Scenario Projections

2.1.1 Strategic Options for Transforming the Electricity Sector

The three strategic options that are available for transforming the German electricity sector towards high shares of RES-E include (i) increasing domestic RES-E production, (ii) decreasing electricity demand by means of progress in energy efficiency, and (iii) increasing RES-E imports. The following investigates to which extent the mitigation scenarios exploit each of these strategic options.

To start with the central question of which level of RES-E production is required, Figure 2 reveals at a first glimpse that no unambiguous answer can be given by the scenario projections. The only robust conclusion that can be drawn is that domestic RES-E production will need to continue the upward trend of earlier decades and at least double until 2050 as compared to the de facto production of 120 TWh in 2011. However, significant discrepancies arise between the individual scenario projections. While the scenarios already suggest RES-E levels of 200-350 TWh in 2020, the spread in long-term projections increases up to as much as 250-700 TWh in 2050. Interestingly, the scenario projections are scattered rather evenly within the range spanned by the lowest and highest RES-E expansion pathway. Whether RES-E production ought to increase by factor two or five over the coming four decades does make a considerable difference for the design and volume of required RES-E support schemes and, correspondingly, on the future size of the domestic RES-E market, as well as for the magnitude of the concomitant burden from infrastructure and RES-E capacity deployment. Pursuing a high RES-E expansion strategy would require a doubling of the domestic

RES-E market already in the coming decade and thus called for timely action. On the contrary, a low RES-E expansion strategy allowed three more decades for the same development.

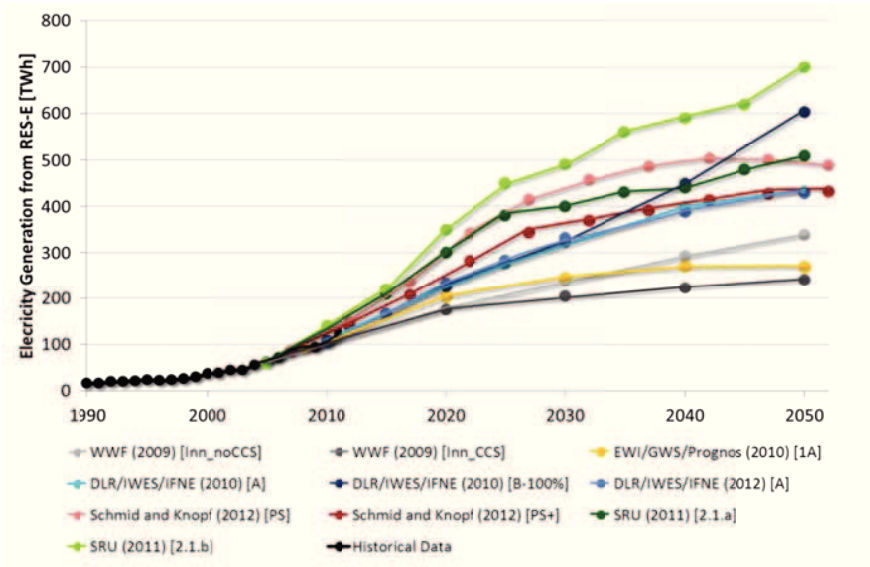

Figure 2. Electricity production from domestic RES-E; includes historical data (BMU, 2012b) and projections from a selection of model-based, long-term mitigation scenarios.

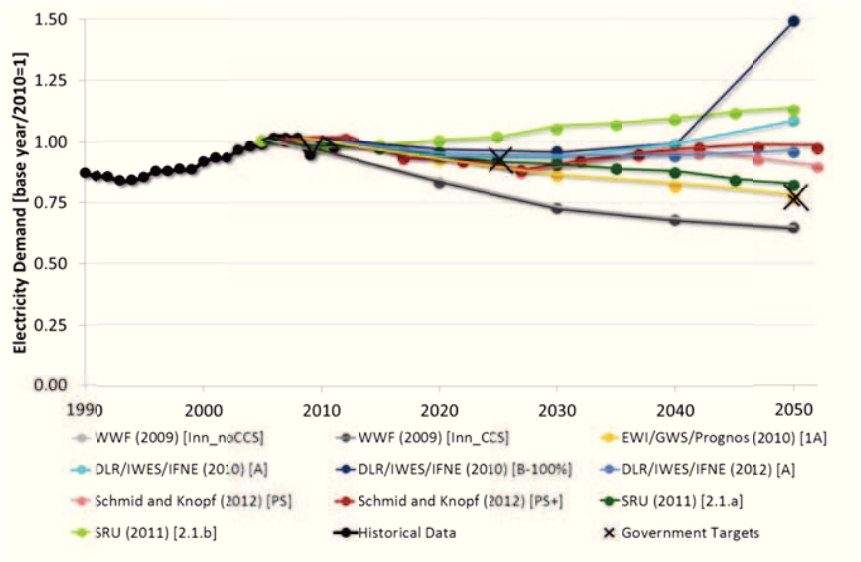

Figure 3. Normalized Electricity Demand; includes historical data (BMWi, 2012) with [2010=1] and projections from a selection of model-based, long-term mitigation scenarios with [base year = 1].

The three by far lowest RES-E expansion scenarios are at the same time those that project the lowest electricity demand, i.e. substantial improvements in energy efficiency. As Figure 3 illustrates, they project reductions of 25%-35% in 2050 compared to 2010. Hence, according to the scenarios, an

energy strategy that relies on low domestic RES-E production must at the same time induce a decisive turnaround in energy efficiency trends: German electricity demand has been increasing by 20% over the past two decades, albeit stagnating in the recent years. However, this development must be attributed to the global financial crisis rather than to dedicated efficiency policies (BMWi, 2010). Such a deliberate energy saving strategy is also favored by the German Government which aims at a 10% reduction in electricity demand in 2025 and 25% in 2050 relative to 2008 in its long-term energy concept (Federal Government, 2010). It needs to be acknowledged that substantial improvements in energy efficiency are not only assumed for scenarios displaying a decreasing electricity demand in Figure 3, but also to a certain extent for those which remain stable over time. GDP is projected to grow continuously in all scenarios, so a stable or slightly decreasing electricity demand is tantamount to a decoupling process of electricity consumption from economic growth or in other words increasing energy efficiency. The upward trend in electricity demand of the DLR/IWES/IFNE (2012) scenarios between 2040 and 2050 is due to additional electricity demand of the emerging electric transport sector. Overall, domestic RES-E production and energy efficiency ambitions appear to be inversely related.

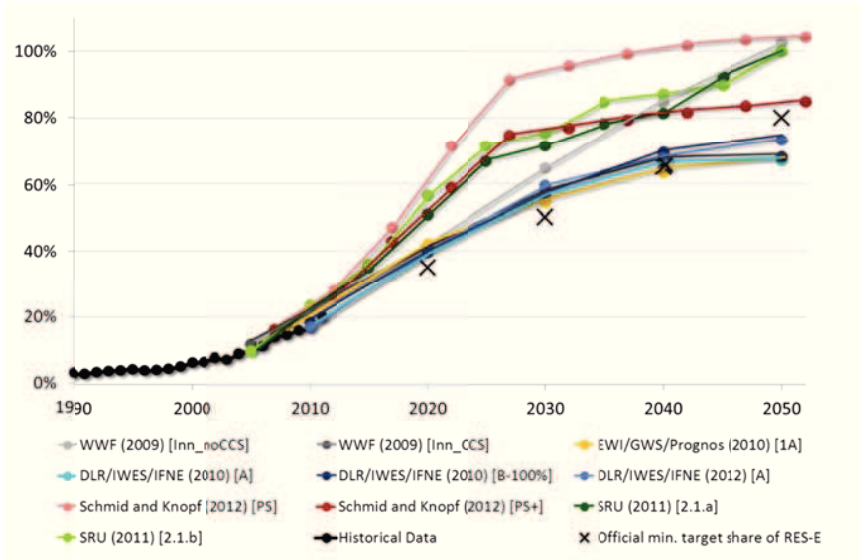

Figure 4. Share of domestic RES-E production in German electricity consumption/production (depending on the data provided); includes historical data (BMU, 2012b; BMWi, 2012) and projections from a selection of model-based, long-term mitigation scenarios. Crosses indicate official minimum targets shares of RES-E in electricity provision as formulated in §1(2) of the Renewable Energy Sources Act – note that they additionally allow for RES-E imports

This impression is corroborated by Figure 4 which depicts the share of domestic RES-E in German electricity consumption/production (depending on the data reported). Even the low RES-E expansion scenarios achieve a domestic RES-E share as high as 70% by 2050. A stunning feature of Figure 4 is

that half of the scenarios follow almost the same linear trajectory just above the Government's targets until 2040, corresponding to a linear increase extrapolating the recently observed growth rate: 15 percentage points per decade. It needs to be mentioned that due to exploiting the strategic option of RES-E imports these scenarios are still consistent with the Government target in 2050. The four scenarios that do not rely on electricity imports display a significantly faster acceleration in the share of RES-E over the next two decades and reach the Government's 80% minimal target share of 2050 as early as 2025 to 2035. A total of four scenarios achieve a RES-E share of 100% in 2050. Since all scenarios project RES-E shares between 40-70% as early as 2020, a deliberate progress in the deployment of system integration options is presupposed for their feasibility (see Section 2.2.2).

As has already been mentioned, several scenarios exploit the strategic option of RES-E imports. This would imply that Germany turned from a net exporter of electricity towards a net importing country with 50-200 TWh in 2050 (Figure 5). The scenarios assume that this imported electricity is produced from RES-E in European countries; DLR/IWES/IFNE (2010; 2012) additionally consider imports from the Middle East North Africa (MENA). EWI/GWS/Prognos (2010) in principle also consider nuclear electricity imports; however, their share is not spelled out. The publications motivate RES-E imports by putting forward the exploitation of more profitable potentials outside of Germany. Technically, extensive imports presuppose that a surplus of RES-E production in exporting countries is actually achieved and the physical integration of the European and/or MENA electricity market is accelerated, implying the expansion of transmission infrastructure and interconnectors. Further, on a political level this requires that energy security considerations, which are currently a sovereign domain, are raised to a transnational level in a cooperative manner.

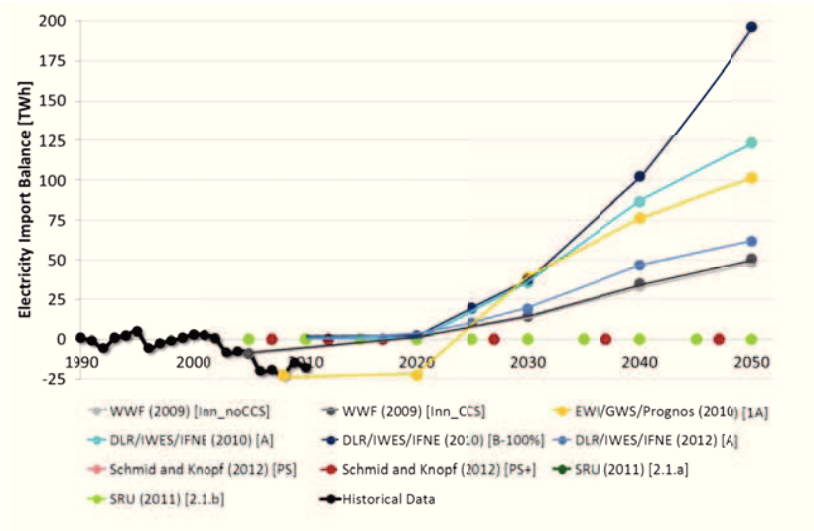

Figure 5. Electricity import balance; includes historical data (BMWi, 2012) and projections from a selection of model-based, long-term mitigation scenarios. Imports are assumed to be produced with RES-E technologies.

Table 2. Stylized comparative account of the extent to which the scenarios exploit each of the three strategic options for transforming the German electricity sector towards high shares of RES-E.

Scenario / Strategic Option	Domestic RES-E	Energy Efficiency	RES-E Imports
(WWF, 2009) [Inn_CCS]	+	+ + +	+
(EWI/GWS/Prognos, 2010) [A1]	+	+ + +	+ +
(WWF, 2009) [Inn_noCCS]	+	+ + +	+
(DLR/IWES/IFNE, 2012) [A]	+ +	+ +	+
(SRU, 2011) [2.1.a]	+ +	+ + +	
(Schmid and Knopf, 2012) [PS]	+ +	+ +	
(Schmid and Knopf, 2012) [PS+]	+ +	+ +	
(SRU, 2011) [2.1.b]	+ + +	+	
(DLR/IWES/IFNE, 2010) [A]	+ +	+	+ +
(DLR/IWES/IFNE, 2010) [B-100%]	+ + +	+	+ + +

To summarize, the investigation has revealed that the scenarios exploit the strategic options of (i) increasing domestic RES-E production, (ii) decreasing electricity demand by means of progress in energy efficiency and (iii) increasing RES-E imports to a very different extent. This finding is visualized in Table 2, which gives a stylized comparative account on the extent to which the scenarios emphasize each strategic option. In order to condense information, the spread of the scenario projections for each option in 2050 is divided by three and then scenarios are attributed their respective category rating. Note that for electricity demand, the outlier of the DLR/IWES/IFNE (2012) [100%-SH2] scenario was not considered for calculating the spread. The scenarios can be clustered in three groups, which differ with respect to the energy strategy they embody. The first group heavily relies on exploiting energy efficiency potentials to reduce electricity demand, which is satisfied by relatively low domestic RES-E production and moderate RES-E imports. A second group refrains from imports and balances moderate to high domestic RES-E production against high to moderate energy efficiency improvements. The third group puts a similar focus on domestic RES-E production but compensates relatively higher electricity demand with RES-E imports. Thus, the target of reaching high shares of RES-E in the German electricity sector can be achieved with distinct energy strategies – according to the scenario projections.

2.1.3 RES-E Technologies

Since an increase in domestic RES-E production is exploited in all scenarios, a highly relevant question is which RES-E technologies are of major importance for the German energy transition. In order to abstract from the diverging absolute levels of domestic RES-E production in the different scenarios Figure 6 displays the percentage share of each RES-E technology in total cumulative RES-E production over the period 2010-2050. Hydropower is excluded from the analysis as the domestic potential is already exploited in Germany. At a first glimpse, Figure 6 reveals that electricity generation from wind is the most important pillar of the future technology mix in all scenarios. Together, wind onshore and offshore contribute 55-70% of cumulative domestic RES-E production between 2010 and 2050. With the exception of the SRU (2011) scenarios where offshore plays a dominant role, wind onshore and offshore contribute in equal parts. Electricity production from biomass provides 10-30%. Biomass is in fact a dispatchable RES-E technology, which plays an important role in balancing fluctuations from the variable technologies wind and solar. Yet, the potential of biomass is limited mainly due to ecological concerns (Nitsch et al., 2004). Solar PV, the most expensive technology in terms of levelized cost of electricity today (Fischedick et al., 2011), does ostensibly not play a major role in either of the scenarios with as little as 3-16% of cumulative domestic RES-E production. Finally, geothermal electricity generation plays a substantial role only in those scenarios that refrain from RES-E imports. Hence, in relative terms the scenarios suggest that wind offshore and onshore are the most important technologies, closely followed by biomass, and to a lesser extent solar PV as well as geothermal.

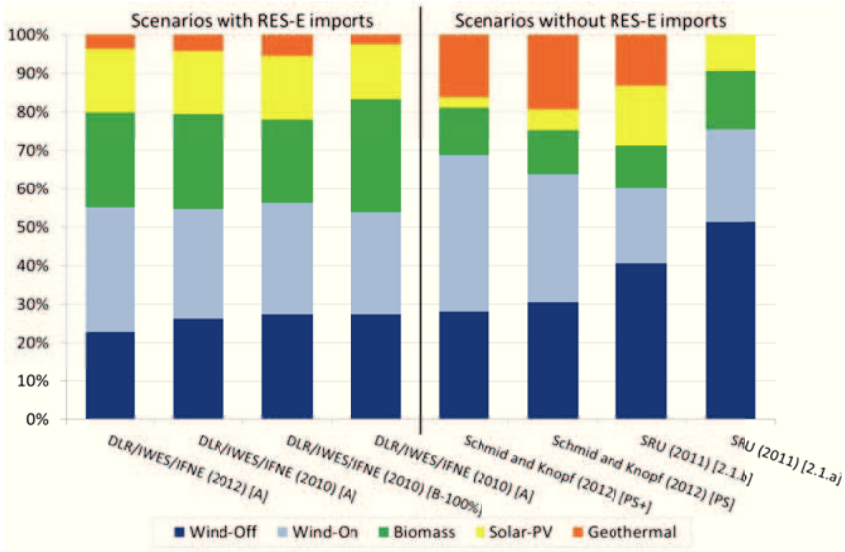

Figure 6. Shares of individual RES-E technologies in cumulative domestic RES-E production over the period 2010 to 2050.

Given the large spread in absolute domestic RES-E production across scenarios discussed above, it does not come at a surprise that the projected developments of the individual technologies follow diverse pathways over time. When comparing de facto electricity production from solar PV and wind offshore with scenario projections, it is eye-catching that for the former, reality has overtaken model projections – while the opposite is true for the latter (Figure 7). Since the Renewable Energy Sources Act was installed in 2000, capacity deployment of solar PV in Germany increased tremendously from 0.076 to 25 GW in 2011 (BMU, 2012b). On the contrary, a substantial deployment of wind offshore could so far not be triggered by the Renewable Energy Sources Act and installed capacity in 2011 accrued to as little as 280 MW (BMU, 2012b). Currently, planned offshore projects accrue to 9 GW which is far below the tentative Government target of 25 GW by 2030 (Federal Government, 2010). While an analysis of why the projections are diverging so much is postponed to Section 3, for the moment it suffices to realize that, according to the scenario projections, for achieving high shares of RES-E in the electricity sector the wind offshore market needs to develop urgently and overtake the solar PV market in size within the coming decade.

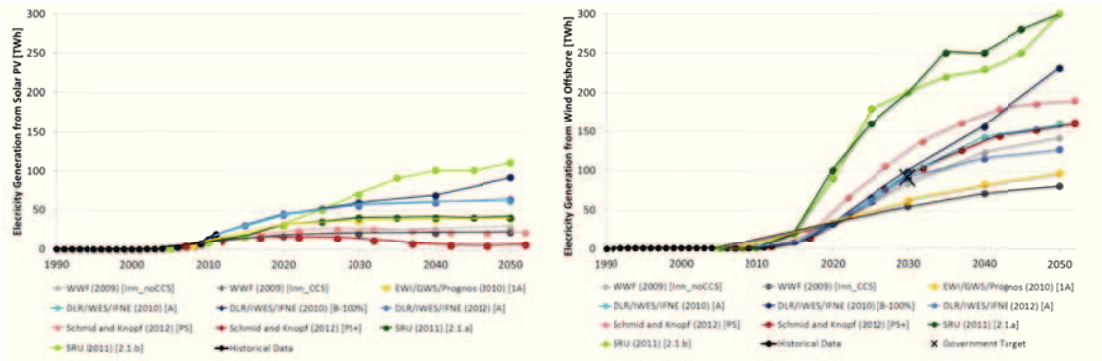

Figure 7. Electricity Production from Solar PV and Wind Offshore; includes historical data (BMU, 2012b) and projections from a selection of model-based, long-term mitigation scenarios. The cross indicates the tentative government target of 25 GW capacity in 2030 (Federal Government, 2010), which is converted to production with a capacity factor of 0.43 (the average number for 2020 across scenarios)

2.1.3 RES-E Capacity Investments

How much needs to be invested in RES-E capacities? Most publications refrain from providing total RES-E capacity investments, however, the majority reports specific investment costs in €/kWh as well as installed capacities in GW for individual years between 2010 and 2050. In order to make investment costs comparable, we perform the following calculation for all scenarios: We derive specific investment costs and capacity additions for every fifth year in the period by linear interpolation, under the assumption that capacities are fully depreciated after 20 years. By multiplying specific investment costs with the capacity additions, total investment costs for every

fifth year can be identified. We further assume that investments within five-year periods are distributed uniformly. The resulting annual investment flows are converted to their present value with a discount rate of 3%. Figure 8 reports the results for the short-term (2010-2020) and long-term (2010-2050), together with the already incurred investments of 2010 and 2011.

The present value of total investment costs into RES-E capacities over the next decade is within the range of 80-120 Bn €. Interestingly, upon a closer look, the order of scenarios in terms of investment costs does not coincide with the order in terms of RES-E production for the year 2020 as displayed in Figure 2. Given the similarities in technology shares, differences in assumptions on specific investment costs and average annual full load hours appear to be more important drivers for the scenarios' present values of RES-E investments than total RES-E production, which is counterintuitive. For the period 2010-2050, this observation holds even more pronouncedly and the spread in present values increases up to 180-350 Bn €. Yet, the scenario with the highest present value of total RES-E investments attains only a moderate level of domestic RES-E production in 2050 as compared to the other scenarios. Section 3 investigates this issue in further detail.

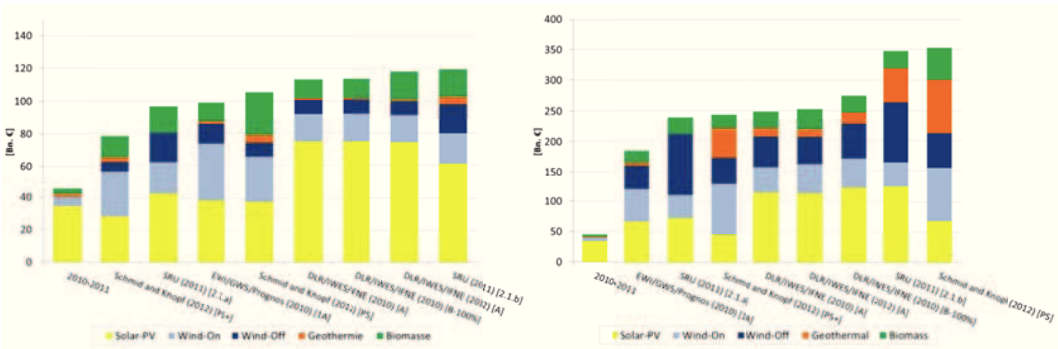

Figure 8. Present value of RES-E capacity investments over the period 2010-2020 (left) and 2010-2050 (right) at a discount rate of 3%; included are only scenarios for which specific investment costs are reported. Undiscounted data for the years 2010 and 2011 are from BMU (BMU, 2011; BMU, 2012a); historical data on wind offshore is lacking

Across scenarios a disproportionately high fraction of investments into RES-E capacities occurs in the coming decade, given that the present values for 2010-2020 account for 30-54% of the respective present values for 2010-2050. An equal distribution across decades implied a value of 25%. Thus, the scenarios suggest that the transformation of the German electricity sector towards high shares of RES-E requires a decisive and timely investment effort than may subsequently be relaxed. This is especially the case in those scenarios that heavily exploit energy efficiency potentials. Those scenarios which refrain from RES-E imports and exploit energy efficiency potentials to a lesser extent require higher investments into RES-E capacities also in the later decades. Relating annual RES-E

investments to GDP in the respective year corroborates this finding: While the share amounts to 0.4-0.6% of GDP across scenarios in the next decade, it decreases to 0.1-0.5% by 2050.

In the years 2010 and 2011 investment volumes of 24.5 Bn € and 21 Bn € into RES-E capacities were attracted by the Renewable Energy Sources Act (BMU, 2011; BMU, 2012a), corresponding to 0.98% and 0.81% of GDP (Statistisches Bundesamt, 2012). Thus, the required short-term investments appear feasible if investment dynamics continue the trend. In the scenarios investments into solar PV heavily dominate over the period 2010-2020, with 37-66% of total RES-E capital investments. This is also the case for the de facto investments of 2010 and 2011 in which solar PV had a share of 77%. The disproportionate share of solar PV in historical investments is due to the fact that the specific investment costs of solar panels have decreased continuously by more than 60% since 2006 (BSW Solar, 2012), but feed-in tariffs have been reduced only sporadically. This resulted in double-digit profit margins and solar-PV attracted as much as 35 Bn € of capital investments in 2010 and 2011 alone. However, according to the scenarios, capital investments need to diversify towards the other RES-E technologies in the near-term future, especially towards wind onshore and offshore.

2.2 Barriers to Implementation

Despite the numerous discrepancies between scenario projections, the meta-analysis has revealed several robust findings across scenarios. These include that in order to transform the German electricity sector towards high shares of RES-E, energy efficiency potentials need to be exploited more than has been the case to date, system integration measures for uncertain, fluctuating and spatially dispersed RES-E technologies need to be in place in due time, and wind offshore deployment has to accelerate significantly. Yet there is evidence of a number of behavioral, institutional and engineering obstacles that need to be overcome in order to realize the energy strategies suggested by the scenarios.

2.2.1 Energy Efficiency: The Behavioral and Market Failure Challenge

Energy efficiency constitutes a controversial policy domain for which it is highly unclear whether ambitious targets can be realized. A long-standing debate in the literature has observed numerous policy puzzles, the most prominent being the rebound effect. It postulates that an increase in energy efficiency of a specific energy service may lead to a direct increase in the demand of that service or

indirectly increase the demand of other energy-intensive services and thus to an increase in net energy consumption (Sorrell et al., 2009). Attempts to measure the rebound effect is subject to numerous methodological and data measurement problems, however, a recent literature survey suggests that the direct rebound effect may reduce energy efficiency projections of engineering models by as much as 30% (Sorrell, 2007). In any case, rebound effects should be taken into account when designing energy efficiency policy and may be mitigated through carbon taxes or mitigation caps – that is through higher prices on carbon-intensive energy (Sorrell, 2007). A further puzzle is that many proposed energy efficiency policies are in fact energy saving policies targeted at forcing the incumbent, regulated utilities to implement energy efficiency programs which after all reduce the demand for their product (Brennan, 2011). Alternative business models seem necessary to exploit energy efficiency opportunities, e.g. energy contracting. In Germany, one company started to offer energy contracting for consumers, but could not establish themselves on the market and withdrew their activities in the end-customer segment, now focusing only on organizational and institutional customers (Kofler Energies Power AG, 2011).

A collection of market and behavioral failures to explain the difficulties in promoting energy efficiency have been suggested in literature (e.g. Sorrell et al., 2004; Gillingham et al., 2009; Thollander et al., 2010). Many of the identified market failures (e.g. environmental externalities, average-cost electricity pricing, liquidity constraints, R&D and learning-by-doing spillovers) are not unique to energy efficiency, thus they call for a broader policy response including carbon pricing, innovation policies and electricity market reforms. Information and behavioral failures, such as lack and asymmetry of information, principal-agent problems, split incentives, hidden costs or bounded rationality on the other hand call for more specific energy efficiency policies (Gillingham et al., 2009). In sum, relying on pivotal increases in energy efficiency for mitigation appears to be a risky strategy – given the evidence.

2.2.2 System Integration: The Institutional and Engineering Challenge

For accommodating increasingly high shares of wind and solar PV which are uncertain, fluctuating and spatially dispersed RES-E technologies system integration measures need to be in place in due time. In order to guarantee system stability electricity demand and supply need to be matched at any time and at any place, which becomes increasingly challenging with growing shares of RES-E. Technical solutions include an extension of (i) power grid infrastructure for transporting electricity to demand centers and large-area pooling of fluctuations, (ii) dispatchable generation capacities to

provide short-term balancing as well as back-up capacities in low RES-E feed-in periods, (iv) demand side measures to reduce peak load, (iii) storage capacities to cope with fluctuations on both short and long time-scales, thereby avoiding the need for curtailment in high RES-E periods, and (v) improved operational and planning methods (Sims et al., 2011). Currently, none of the options is deployed at a sufficient level to integrate rising shares of RES-E as projected by the mitigation scenarios into the German power grid (dena, 2010) – the stability of German power grids was already critical in the winter 2011/2012 (Federal Network Agency, 2012).

In order to guarantee stability and security of electricity supply in the future the deployment of an optimal portfolio of system integration measures needs to be incentivized. Doing so requires adaptations of the institutional framework conditions such as speeding up approval procedures for power grid extensions (dena, 2010), reforming the market design of control power markets (Federal Network Agency, 2012) and introducing capacity markets to ensure the profitability of dispatchable generation units (Cramton and Ockenfels, 2012). Also, the pricing system for end customers will need to be re-designed in a more flexible fashion, e.g. real-time prizing, to incentivize demand side measures (Sims et al., 2011). As regards electricity storage most available technologies are immature and still require considerable research and development effort to enable their large-scale deployment (ETG Task Force Energiespeicher, 2008). The only short- and long-term storage technology that constitutes a profitable investment today is pumped hydro storage; however, the German potential is too small to do the job alone (ETG Task Force Energiespeicher, 2008). A controversially discussed possibility is to rely on the huge reservoir capacities in Norway for long-term storage in a European integrated grid, which is e.g. assumed by the SRU (2011) scenarios. In sum, providing sufficient system integration measures for high shares of RES-E requires decisive reforms of institutional framework conditions and technological progress especially regarding electricity storage.

2.2.3 Wind Offshore: The Challenge of Raising Capital

As Section 2.1.3 has revealed, the German feed-in-tariff scheme has incentivized a disproportionate share of solar PV in total RES-E investments in the past; however, according to the scenarios a diversification into other RES-E technologies, particularly wind offshore, is necessary in the future. Since solar PV constitutes a modular, low-risk and low-maintenance technology that is frequently installed in small scales, it is perfectly accessible to the small investor: Private persons and farmers owned as much as 51% of total RES-E capacities in 2010 (trend:research, 2011). On the contrary,

wind offshore constitutes a centralized, high-risk and high-maintenance technology that is only worthwhile installing at large scale. A decisive growth in wind offshore capacities thus requires tapping the capital resources of industry and institutional investors, or pooling private investments.

Either source of capital will only be accessible if the return on investment is deemed sufficiently certain, i.e. projects are assessed as profitable. Because of currently small and uncertain returns on investment, wind offshore projects in the German waters are of interest only to strategic investors but not to financial investors (Richter, 2009). Due to the Wadden Sea National Park only far-shore projects are allowed for in the North Sea, which has the larger wind offshore potential as compared to the Baltic Sea. Increasing water depths and distance to shore are the main influencing factors for investment costs (Prässler and Schaechtele, 2012), rendering projects in less challenging sites outside of the German seas more interesting for profit-seeking investors. In fact, German far-shore sites are expected to deliver an acceptable return on investment only upon deployment of particularly high yield wind turbines with 5 MW capacity (Zeelenberg and van der Kloet, 2007). Only 37 of these turbines have been installed worldwide to date, of which 29 are in Germany (IWES, 2012). The fact that 5 MW turbines are still an immature technology discourages project developers, banks, insurances and financial investors (Richter, 2009). In RES-E markets, proven reliability of a technology is found to be a necessary condition for investing in it (Masini and Menichetti, 2012). Gaining experience with 5 MW turbines is thus a prerequisite for making the German offshore market accessible to financial investors and will need to be pursued by strategic investors such as large utilities and sufficiently incentivized by tailored policy measures.

3. From Assumptions to Scenarios

For developing a robust energy strategy for the German electricity sector it is of particular interest to understand why the scenarios exploit the strategic options of increasing domestic RES-E, decreasing electricity demand and increasing RES-E imports to such different extents. Does it depend on input assumptions, inter alia particular targets, or is it due to different modeling approaches? In order to elucidate reasons and drivers for the different scenario projections Section 3.1 investigates the methodologies by which the scenarios were modeled and Section 3.2 compares underlying techno-economic assumptions. Furthermore, the following comes back to two questions that were raised in the meta-analysis: Why are solar PV and wind offshore deployment so diverse across scenarios? Are differences in techno-economic assumptions decisive for the scenarios' projections of total RES-E capacity investment requirements?

3.1 Modeling Methodology

While all publications analyzed in this paper rely on quantitative modeling for deriving the mitigation scenarios, they differ with respect to how electricity demand, deployment pathways of RES-E capacities and imports are determined. The main question in this context is whether they are defined as model input and determined exogenously, or whether they are a model result, or both. The latter is common practice when soft-coupling partial models, which is advantageous when a strong focus is put on technological detail, but comes at the cost of impeding systemic feedback. As can be seen immediately from Table 3, none of the publications yield demand, capacities and imports as model results simultaneously. In fact, to our knowledge there exists to date no model for Germany that is capable of providing the necessary sectorial detail and regional and temporal scope, likely due to numerical constraints. Each publication opts for a different approach, thereby abstracting from reality in distinct respects.

Table 3. Overview of how electricity demand, RES-E capacities and RES-E imports are determined in the publications.

Publication	Electricity Demand		RES-E capacities	RES-E Imports
(WWF, 2009)	Model result (from bottom-up simulation)	Model input (to dispatch model)	Model input (to dispatch model)	Residual value
(EWI/GWS/Prognos, 2010)	Model result (from bottom-up simulation)	Model input (to dispatch model)	Model input (to dispatch model)	Model result (from dispatch model)
(DLR/IWES/IFNE, 2010; 2012)	Model result (from "quantity framework")		Model input (to "quantity framework")	Model result for selected years (from EU electricity sector model)
(Schmid and Knopf, 2012)	Model result (from integrated welfare maximization)			Not considered
(SRU, 2011)	Model input (to EU electricity sector model)		Model result for 2050 (from EU electricity sector model), Interpolation before	Model result for 2050 (from EU electricity sector model)

One of the most important variables in energy strategies is the absolute magnitude of future electricity demand. Here, the approaches range from a detailed, bottom-up representation over an economic top-down production function to treating demand as exogenous by relying on projections of other publications. The first extreme is pursued in both WWF (2009) and EWI/GWS/Prognos

(2010) which apply the same detailed bottom-up simulation model of the Prognos AG, consisting of a variety of sectorial sub-modules that generate differentiated projections of the energy demands of the industry and the residential and commercial sectors. One of the model outputs is the annual electricity demand along with its load profile. Bottom-up models take on an engineer's perspective by incorporating detailed descriptions of technologies while assuming market adoption of the most efficient technologies (Hourcade and Robinson, 1996). These models postulate that market forces do not operate perfectly and frequently identify an efficiency gap between the current technology penetration and best available techniques. Suggested mitigation policy implications are mainly to remove barriers to adoption of the best available technique. In the global energy system models literature, bottom-up models have been found to be highly optimistic regarding the technical mitigation potential, due to picking "low-hanging fruits", which are in fact not picked today (Grubb et al., 1993; Hourcade and Robinson, 1996).

The highly optimistically decreasing electricity demand projections postulated in both the WWF (2009) and EWI/GWS/Prognos (2010) scenarios are thus most likely an implication of using a bottom-up demand model. The "quantity framework" applied in DLR/IWES/IFNE (2010; 2012) is a spreadsheet simulation tool that is similarly assumption-driven, but not as detailed as the Prognos demand model. Schmid and Knopf (2012) apply the hybrid energy economy model REMIND-D (Schmid et al., 2012) which determines energy demand endogenously in a top-down approach by means of a calibrated and parameterized production function. Here, electricity demand can respond to changes in the energy system, e.g. in terms of rebound effects. Finally, SRU (2011) choose electricity demand pathways as entirely exogenous input for their European electricity sector model REMix (Scholz, 2010). They motivate their choice of trajectories as the upper and lower boundary of the range projected by existing scenarios.

For determining the technology mix in the electricity sector the publications either rely on detailed dispatch modeling, spreadsheet calculation, or optimization methods. Both WWF (2009) and EWI/GWS/Prognos (2010) apply a dispatch model albeit adopting a different regional scope with Germany only and Europe, respectively. Dispatch models determine the cost-minimal dispatch of power plants for covering residual load, i.e. the demand time series minus priority feed-in of fluctuating RES-E technologies. Hence by construction both RES-E capacity deployment and the associated feed-in need to be determined exogenously before running a dispatch model. RES-E capacities are also exogenous to the "quantity framework" of DLR/IWES/IFNE (2010; 2012). None of the publications provide in-depth information on the rationale behind the selected RES-E deployment pathways and feed-in projections. WWF (2009) relies on the RES-E projections of DLR

(2008), an earlier version of DLR/IWES/IFNE (2010; 2012). EWI/GWS/Prognos (2010) state: "The scenario construction of the electricity generation sector is further based on a model of renewable energies in Europe that represents several RES-E technologies in a regionally differentiated manner." (p. 28). Yet, it is unclear how particular technologies and their deployment levels were chosen. DLR/IWES/IFNE (2010) state: "The capacity deployment path of RES-E technologies results from an extrapolation of the historical dynamics, under the assumption of priority feed-in for RES-E technologies until 2050." (p. 46). Here, for selected years the technical viability of the chosen technology mix is validated with the simulation tool SimEE; however, this does not replace an endogenous economic optimization approach. In sum, none of the three publications that consider deployment and feed-in of RES-E technologies as exogenous input motivate their choices explicitly.

An important implication of the exogenous and sparsely motivated determination of RES-E technology deployment pathways and associated RES-E feed-in is that these scenario projections are beyond analytical traceability. Thus, the resulting scenarios are entirely normative scenarios that aim at delivering particular targets. Underlying input parameters are determined via expert judgments so as to achieve the targets in an optimal way. This is particularly problematic if the assumptions are not made explicit and/or are at odds with systemic effects that arise upon endogenous consideration of RES-E deployment and feed-in, an issue that is elucidated below.

In Schmid and Knopf (2012) and SRU (2011), RES-E capacities are determined endogenously. They are an output of the optimization models REMIND-D and REMix, respectively. REMIND-D adopts a social planner perspective with perfect foresight and determines the welfare-optimal RES-E deployment pathway for Germany in five-year time steps. The variability of wind and solar PV is addressed by means of a residual load duration curve (RLDC) approach (Ueckerdt et al., 2011). The REMix model covers all of Europe and Northern Africa and determines the cost-optimal dispatch of RES-E technologies, based on an exogenous target share, and considering their temporal and geographical availability as well as electricity grid and storage options explicitly (Scholz, 2010). For the SRU (2011) scenarios only the year 2050 was analyzed with REMix, imposing a target share of RES-E of 100%. The deployment path between 2010 and 2050 was derived by interpolation. Hence, nothing can be said on the optimality of the transitional RES-E deployment here. Yet, the results of Schmid and Knopf (2012) indicate that a much faster increase in RES-E production over the next decades would be optimal from an integrated welfare maximization point of view (see Figure 1). Also, the share of solar PV is much lower in their scenarios – the only ones that consider system integration effects and intertemporally optimal capacity deployment over time endogenously.

Finally, the role of RES-E imports primarily depends on the regional scope of the applied model(s). As the dispatch model in WWF (2009) only represents Germany, imports are a residual figure after considering demand, domestic RES-E production and cost-minimal thermal electricity production. In EWI/GWS/Prognos (2010) the dispatch model has 12 regions and calculates cost-optimal imports and exports. In DLR/IWES/IFNE (2010; 2012), it is not entirely clear how imports are determined. Nonetheless, they are validated with the European electricity sector model REMix which establishes cost-minimal generation and associated import and export flows for each country. Schmid and Knopf (2012) abstract from imports as REMIND-D is a closed economy model. In the selected scenarios of SRU (2011), net electricity imports are imposed to be zero.

In sum, this Section has elucidated that the choice of modeling methodology and particularly exogenous assumptions and predefined normative targets are decisive drivers for the strategy relevant variables domestic RES-E production, electricity demand and RES-E imports.

3.2 Techno-Economic Assumptions

Two kinds of assumptions are of special importance for the profitability of RES-E technologies: The development of specific investment costs and the yield of installed capacities in terms of average annual full load hours (FLH). A common denominator in the publications is that they assume technological learning processes to occur, in particular learning-by-doing (cp. Junginger et al., 2010). Technological learning entails a decrease in specific investment costs of innovative technologies as they reach maturity. Learning effects have been detected empirically by means of identifying a statistical relationship between investment costs and cumulative capacity, a so-called experience curve, that is quantified by a parameter termed the learning rate, and for which a coefficient of determination (R^2) characterizes the explanatory power (cp. Neij, 2008; Junginger et al., 2010). The learning rate expresses the rate by which specific investment costs decrease upon a doubling of cumulative capacity. For modeling purposes regression estimates of learning rates are interpolated into the future and either serve as an input to the model, if learning is modeled endogenously, or as an orientation to estimate cost reductions exogenously. Thus, the learning rate constitutes a central driver for projected RES-E capacity investment requirements.

Table 4 presents the learning rates that were assumed in the mitigation scenario publications under analysis. A stunning feature is that only two publications give a full account of the learning rates, and two publications do not report them at all. This lack of transparency constitutes a major obstacle to tracing the differences in RES-E deployment across scenarios. Nevertheless, two observations yield

insights. The learning rate of solar PV is rather similar in those scenarios which report learning rates and thus cannot be held responsible for the differences in deployment patterns. The learning rate for wind offshore in SRU (2011) is set at the highest value of all scenarios with 18.6% and most likely explains the strong expansion path of offshore deployment in their scenarios. Generally, the learning rates in the SRU (2011) scenario are much higher than in the other scenarios.

Table 4. Learning rate assumptions of the different RES-E technologies as reported in the publications.

Publication	Solar PV	Wind Onshore	Wind Offshore	Geo-thermal	Biomass
(WWF, 2009)	n.a.	n.a.	n.a.	n.a.	n.a.
(EWI/GWS/Prognos, 2010)	n.a.	n.a.	n.a.	n.a.	n.a.
(DLR/IWES/IFNE, 2010)	20%	n.a.	10%	n.a.	n.a.
(DLR/IWES/IFNE, 2012)	20%	n.a.	10%	n.a.	n.a.
(Schmid and Knopf, 2012)	20%	6%	12%	0%	0%
(SRU, 2011)	25.9%	11.5%	18.6%	n.a.	2.2%

Table 5. Average annual full load hours (FLHs) in 2010/2050 as reported in the publications. In Schmid and Knopf (2012) these numbers are not reported; they are provided by the authors here

Publication[Scenario]	Solar PV	Wind Onshore	Wind Offshore	Geo-thermal	Biomass
(WWF, 2009)	n.a.	n.a.	n.a.	n.a.	n.a.
(EWI/GWS/Prognos, 2010)	900-1000/ 1000-1500	1200-2800/ 1400-3900	2000-4200/ 3000-5500	n.a.	n.a.
(DLR/IWES/IFNE, 2010)	909/946	2050/2550	3200/3900	6100/6645	7030/6725
(DLR/IWES/IFNE, 2012)	n.a.	n.a.	n.a.	n.a.	n.a.
(Schmid and Knopf, 2012)[PS]	970/850	2000/1500	3500/3000	7700/3700	6200/1500
(Schmid and Knopf, 2012)[PS+]	970/740	2000/1600	3500/3400	7700/5200	7500/7200
(SRU, 2011)	800/1000	1500/2500	3000/4500	7500	7000

However, literature provides ample evidence that the application of learning rates for projecting RES-E investment costs suffers from serious shortcomings. The estimation of learning rates is highly sensitive to the timing of the underlying data both in terms of when the forecast was made and the duration of the data set (Nemet, 2009). Furthermore, while the R^2 as an indicator for the explanatory power of the estimation is rather high in learning rate estimations for the modular technology solar PV (Junginger et al., 2008), it is very low in estimates for wind offshore, where little data exists (Neij, 2008; van der Zwaan et al., 2011). For wind offshore it has been shown that investment costs

actually increased in the recent years and cost-reductions in the future are assessed as uncertain (Heptonstall et al., 2012). These insights reveal that the practice of using both deterministic and highly optimistic learning rates in scenario development may result in underestimating total RES-E investment requirements for a given projected deployment pathway.

Regarding the scenario assumptions on average annual full load hours (FLHs), Table 5 displays the values reported in the publication for the years 2010/2050. A highly interesting pattern emerges. In all publications that treat RES-E levels as an exogenous variable the FLHs increase significantly over the next four decades. This development is justified by technological progress and maintaining priority feed-in of RES-E production. However, in the Schmid and Knopf (2012) scenarios, which model both RES-E capacity additions and average annual dispatch endogenously with REMIND-D, the FLHs show the opposite tendency and decrease, particularly so in the [PS+] scenario. There are three reasons for this development. First, REMIND-D represents the domestic RES-E potential for each technology by means of a grade structure that postulates that the highest-quality sites are exploited first and then, subsequently, the less efficient sites. With rising capacity deployment this leads to a decrease in FLHs. Second, REMIND-D considers that FLHs of dispatchable capacities decrease significantly with high shares of RES-E due to their role of providing peak load during few periods of the year. In the [PS+] scenario, where CCS plants are available they provide the service. In the [PS] scenario CCS is not available and peak load has to be provided mainly by biomass and geothermal, strongly reducing their FLHs. Third, REMIND-D takes into account the effect that solar and wind capacities need to be curtailed during high production periods if the correlation with demand is disadvantageous. This effect becomes increasingly pronounced with very high shares of RES-E. Since the [PS] scenario attains a 100% RES-E share in 2050, curtailment significantly reduces FLHs particularly for wind offshore. In sum, a considerably higher absolute level of RES-E capacities needs to be in place in this scenario for producing the same level of RES-E production as compared to other scenarios, thereby incurring higher investment requirements. Given that the reasons for decreasing FLHs with increasing shares of RES-E originate in systemic effects that render a sustained priority feed-in questionable, the assumption of increasing FLHs appears problematic.

To summarize the answers on the question of why solar PV and wind offshore deployment is so diverse across scenarios, the analysis of the modeling methodology has shown that for the majority of scenarios this development is determined exogenously and hence beyond analytical traceability. Also, assumptions on learning rates and FLHs do not seem to have a systematic impact. Thus, the question remains largely unanswered. Regarding the question of whether differences in techno-economic assumptions are decisive for the scenarios' projections on required RES-E capacity

investments, the reported numbers for learning rates and FLH convey a clear message: Yes. The assumption of high learning rates results in decreasing specific investment costs. The assumption of increasing FLHs results in relatively lower capacity requirements for equal levels of electricity production. As the discussion above has shown that both assumptions appear overly optimistic, the present values of RES-E capacity investments in Section 2.1.2 are to be consumed with care and are likely to be underestimating actual investments required for realizing the projected levels of RES-E production.

Overall, this section has elucidated that both the choice of modeling methodology and assumptions on learning rates and FLHs have a significant impact on the scenario projections which served as a basis for identifying possible energy strategies for transforming the German electricity sector towards high shares of RES-E in Section 2.1. Thus, a sound evaluation of any energy strategy based on the results of quantitative energy system modeling equally implies an evaluation of the underlying methodological and techno-economic assumptions. In other words, for evaluating assertions of the semantic form "if → then", the analytical quality of the "if" and the "→" is pivotal.

4 Summary and Conclusions

In the first part, this paper investigated a number of strategic questions relevant for the long-term transformation of the German electricity sector towards high shares of RES-E: Which level of domestic RES-E production is required? What is the role of energy efficiency and RES-E imports in this context? Which RES-E technologies are of major importance? How much needs to be invested in RES-E capacities? The analysis was based on a meta-analysis of scenario projections of ten mitigation scenarios drawn from six recent publications. It has been shown that the scenarios exploit the basic strategic options of domestic RES-E production, energy efficiency improvements and RES-E imports to a different extent and can be clustered in three groups.

The first group heavily relies on exploiting energy efficiency potentials to reduce electricity demand, which is accompanied by comparatively low levels of domestic RES-E production and moderate RES-E imports. However, the exploitation of efficiency potentials cannot be steered directly and additionally energy efficiency policies may lead to unintended effects like a direct or indirect rebound. A second group of scenarios refrains from imports and balances moderate to high domestic RES-E production against high to moderate efficiency improvements. The third group puts a similar focus on domestic RES-E production but compensates relatively higher electricity demand with substantial RES-E imports. It needs to be acknowledged that such a strategy requires an

accelerated integration of European and/or MENA electricity markets as well surplus RES-E production for export in these countries. Thus, according to the scenarios the transformation of the electricity sector towards high shares of RES-E can be attained with low, moderate or high levels of RES-E production, depending on the development of electricity demand and RES-E import potential. However, the behavioral and institutional requirements for achieving a decrease in electricity demand are not explicitly considered in most scenarios and may pose significant barriers to implementation of such a strategy.

Regarding technology choice, the scenarios suggest that wind offshore and onshore are the most important technologies, providing 55-70% of cumulative domestic RES-E production over the period 2010-2050. Electricity generation from biomass contributes 10-30% and solar PV 3-16%. Geothermal electricity generation only plays a role in scenarios that refrain from RES-E imports. With increasingly high shares of variable electricity provision from wind and solar, both technical and institutional system integration solutions and measures need to be in place in due time. The majority of scenarios does not consider these challenges explicitly and instead maintain the assumption of sustained priority feed-in for RES-E production, which is highly doubtful from a systems perspective.

A calculation of present values of total investment costs into RES-E capacities indicates a range of 80-120 Bn € for the decade 2010-2020 and 180-350 Bn € for the long-term period 2010-2050. On an annual basis, this corresponds to 0.4-0.6% of GDP over the decade 2010-2020 and decreases to 0.1-0.5% of GDP by 2050. Given that RES-E capacity investments accrued to 0.98% and 0.81% of GDP in 2010 and 2011 (BMU, 2011; BMU, 2012a; Statistisches Bundesamt, 2012), these investment volumes appear feasible if the trend continues. However, the scenarios suggest that the dominant role of solar PV in historical investments will need to be reduced and investments will have to diversify towards the other RES-E technologies. Particularly, the wind offshore market needs to accelerate significantly and overcome the current difficulties in attracting the required financial capital.

Yet, these numbers have to be interpreted with care as overly optimistic assumptions on specific investment costs and average annual full load hours appear to be more decisive drivers for RES-E capacity investment requirements than total RES-E production, which is counterintuitive. The second part of the paper has revealed that more often than not exogenous assumptions and predefined targets – instead of numerical optimization – in the modeling methodology are pivotal drivers for scenario projections, particularly for the deployment pathways and feed-in of RES-E technologies. Thus, the resulting scenarios are beyond analytical traceability and constitute entirely normative scenarios that aim at delivering particular targets. Underlying input parameters are determined via

expert judgments so as to achieve the targets in an optimal way. This is particularly problematic if the assumptions are not made explicit and/or are at odds with systemic effects, e.g. the assumption of sustained priority feed-in of RES-E. These insights corroborate the importance of taking into account the entire argumentation structure of model-based mitigation scenarios, which can be conceived as complex thought experiments of the semantic form "if → then". From this perspective, an explication of the "if" and the "→" is required to attach meaning to the "then" assertion. Further, in order to develop robust energy strategies for transforming the German electricity sector towards high shares of RES-E it is necessary to vary the "if" dimension in future research, i.e. vary assumptions from optimistic to worst case. In this manner, the resulting scenario projections span a robust range of possible energy system futures.

While current mitigation scenarios largely demonstrate that under optimistic assumptions a transformation towards high shares of RES-E is theoretically feasible, future research should also increasingly tackle questions such as: How realistic are these assumptions? What kind of policy measures are required that these assumptions come true? To what extent are energy strategy relevant findings dependent on possibly overly optimistic assumptions? In order to investigate these questions the modeling tools should be improved towards optimizing under high temporal and spatial resolution and considering all sectors of the energy system and their technology options as well as system integration measures and infrastructure requirements in an integrated manner. To enable a scientific discourse on model methodologies, underlying techno-economic assumptions and institutional requirements, future mitigation scenario publications should be elaborating on these issues more transparently and explicitly.

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Chapter 6

Synthesis and Suggestions for Future Research

The guiding theme of this thesis has been to explore how implicit normative considerations in model-based mitigation scenarios can be made explicit in order to adhere to the good principles of scientific policy advice. It strived to realize the second and third stage of the pragmatic-enlightened model (PEM) of the science-policy interface (Edenhofer and Kowarsch, 2012) for the German mitigation policy process, which imply an elaboration of possible policy ends-in-view/means combinations (second stage) and scrutinizing a selection in detail for their possible consequences (third stage) – both in a public debate. This thesis elaborated on mitigation scenarios for Germany that attain the end-in-view of 85% CO_2 emission reduction in 2050 relative to 1990, in line with the target corridor articulated by the German Government (Federal Government, 2010). The scenarios were developed in collaboration between science and civil society stakeholders, taking an analytical-deliberative approach. Further, it scrutinized a selection of mitigation scenarios in detail with respect to the type of energy strategy they embody for transforming the German electricity sector towards high shares of renewable electricity generation and which possible consequences they imply.

The contributions of this thesis to the mitigation scenario literature are fourfold: First, it provides a methodology for developing mitigation scenarios in collaboration between science and civil society that can serve as a starting point for future scenario exercises. Second, it presents a hybrid energy-economy model for Germany that is based on economic theory and for which all input assumptions are made transparent. Third, it contributes three mitigation scenarios for Germany that deal with normative considerations more openly and explicitly than existing scenarios. And fourth, it supplies a comparative meta-analysis of mitigation scenario projections for the German electricity sector.

The following Synthesis summarizes the findings presented in the core chapters of this thesis by answering the research questions posed in the Introduction and concludes the exploration of German mitigation scenarios with suggestions for future research.

6.1 Collaborative Scenario Definition and Evaluation Process

In the first part of this thesis, an exploratory research addressed the challenge of engaging civil society stakeholders in the development process of ambitious mitigation scenarios based on formal energy system modeling. This approach allows for the explicit attachment of normative considerations to technology-focused mitigation options. During consecutive dialogues, civil society representatives framed the definition of boundary conditions for the energy-economy model REMIND-D and evaluated the emerging scenarios with regard to plausibility and social acceptance considerations, corresponding to an analytical-deliberative approach (Stern and Fineberg, 1996; Renn, 1999) in which deliberation frames analysis and analysis informs deliberation. The first set of questions relates to the process itself:

- **What kind of organizational project design is suitable to engage civil society stakeholders in mitigation scenario development? How can stakeholder preferences frame the definition of model-based mitigation scenarios?**

A necessary condition for developing mitigation scenarios based on formal energy system modeling jointly with civil society stakeholders is that functional communication flows are be enabled. Given that quantitative modeling of the energy system relies on strong simplifications for determining numerical solutions, the parameters and variables are as such not meaningful to anyone who is not familiar with the model. In order to allow for communication between civil society stakeholders and scientists and ultimately with the energy system model, several translation steps are necessary. These are potentially impeded by communication gaps that arise from cultural distance between the distinct communities of science and civil society. They differ with respect to their raison d'être, objectives and culture, i.e. values, norms and language. Thus, successful collaboration between civil society and science requires a deliberate preparation phase preceding the interaction phase.

Chapter 2 proposes an organizational project design that takes into account these considerations by means of an interdisciplinary approach that involves both scientists and members of environmental non-governmental organizations (NGOs) as core project partners. It appears natural to foster collaboration between NGOs, rooted in the civil society, and scientists as a starting point, and involve civil society stakeholders in later steps of the process. Due to the distinct professional cultures of the project partners, it is decisive to stimulate their awareness for cultural issues in general and cultural differences in particular. In order to achieve this, it is suggested to organize a core project team that is composed of each a research institution and NGO from at least two countries that do not share the same language. Practical advantages of cross-combining professional cultures with national cultures are that project partners are required to communicate in a non-mother tongue, which fosters awareness for communication gaps like unfamiliar terms and alleviates barriers to clarification requests. Further, as the challenge of domestic mitigation presents itself and is addressed very differently in individual countries, the trans-national perspective helps to reframe and to challenge the purely domestic perspective.

The organizational project design proposed in Chapter 2 consists of four distinct phases that differ with respect to their objectives. The first phase is entirely dedicated to intra-group development of the project team to reduce the cultural distance between project partners and intends to establish a fully functional project team with a common language. This is achieved by consciously passing though the initial stages of group development involving forming, storming and norming that precede the performing stage (Tuckman, 1965). It is suggested to employ formal "wish-lists" that make mutual expectations of project partners explicit and serve as a discussion basis for developing a joint understanding of the collaborative scenario definition and evaluation process to follow.

The second phase of the collaborative scenario definition and evaluation process is concerned with the development of the energy system model. External experts are involved in dedicated workshops for obtaining state-of-the art knowledge on technical details for low-carbon technologies. Thereby, external experts can assess the validity of the quantitative model and have a control function on their scientific quality. Further, in this stage of the scenario definition process the core project partners jointly develop translation rules from "model parameters" to "real-world implications" and vice versa, serving to identify possible direct and indirect consequences of the technology-focused mitigation options that are considered in the energy system model. In this translation process, the technological framework conditions for scenario development are disentangled from the political framework conditions. Here, it

is important to identify which normative considerations are implicit in the energy system model parameter configurations. The translation rules serve as a basis for the stakeholder engagement in the following, third phase of the collaborative process. An important output of the second phase is a detailed model description with a transparent reporting of all input assumptions used to calibrate the energy system model as well as all techno-economic assumptions that determine the characteristics of the technological mitigation options at the model's disposal.

The third phase of the collaborative scenario definition and evaluation process is concerned with the repetitive engagement of civil society stakeholders. It combines deliberative elements (stakeholder dialogues) with analytical elements (formal energy system modeling) and thus takes on an analytical deliberative approach in which deliberation frames analysis and analysis informs deliberation (Stern and Fineberg, 1996; Renn, 1999). In a first set of stakeholder dialogues, civil society representatives are invited to discuss possible direct and indirect consequences of the technology-focused mitigation options at the energy system model's disposal and associated key future developments of energy-system related variables, i.e. political framework conditions for the mitigation scenarios. For different sectors of the energy system a representative sample of civil society organizations is invited; the NGO project partners are responsible for the choice as they are assumed to have a good overview of the civil society landscape. A selection of discussion-stimulating introductory questions is pre-determined by the core project team based on their understanding of which topics particularly subject to normative considerations or subject to societal controversies. After each discussion a questionnaire employing social science methods elicits the stakeholders' judgments and preferences on which developments in the energy system they perceive as likely versus unlikely and desirable versus undesirable from the point of view of their organization. Along with the qualitative information obtained during the discussions and expert judgments from literature, the elicited data serves as a basis for generating sectorial "scenario-building-bricks", referred to as parsimonious narratives in Chapter 4. Parsimonious narratives are developed for those mitigation options for which stakeholders have an opinion and judgments on likely versus desirable developments diverge significantly or the desirability is particularly subject to dissent amongst stakeholders. It is suggested to combine the sectorial parsimonious narratives into integrated mitigation scenarios according to the criteria of likeliness, desirability with consent and desirability with dissent. In order to keep the scenario definition traceable, a selection has to be made by the core project team and not all issues that are addressed in the stakeholder dialogues are reflected in the final mitigation scenarios. Finally, the translation rules developed earlier are employed to define the parameters of the energy system model in such a way as to reflect the combinations parsimonious narratives. The resulting scenarios then carry contextual meaning in terms of normative considerations. In a second set of stakeholder dialogues with the same civil society representatives the integrated scenario results of the energy system model are presented and evaluated in terms of their plausibility and where projected developments could raise concerns about social acceptance. This serves to identify socio-political implications of technology-focused mitigation scenarios.

Finally, the fourth phase of the collaborative scenario definition and evaluation process is concerned with the synthesis of the results and the development of comprehensive scenario reports.

The collaborative scenario definition and evaluation process as sketched above has been carried out in the EU FP7 Project “Engaging Civil Society in Low Carbon Scenarios” (ENCI LowCarb). Doing so required the development of an energy system model for Germany. The author of this thesis developed a hybrid energy-economy model of Germany, REMIND-D. In order to provide transparency, Chapter 3 provided a detailed description of the model setup and the underlying techno-economic assumptions. REMIND-D constitutes a Ramsey-type growth model that determines the intertemporal welfare-optimal development of the German energy system given a set of boundary conditions, i.e. input parameter configurations. An important feature of REMIND-D is that is an integrated energy system model that considers all sectors of the energy system and produces scenario projections as a model output.

The second set of research questions developed in the Introduction is concerned with the results of the exploratory research:

- **Which mitigation scenarios for Germany emerge from the exploratory research and how are they evaluated? What are the key findings for enabling the German energy transition?**

Chapter 4 presents three model-based mitigation scenarios for Germany that were defined and evaluated in a participatory process with 11 and 13 civil society stakeholders from the German transport and electricity sector, respectively. Their background ranged from environmental NGOs over industry and consumer associations, topic-related interest groups, urban planning and trade unions to industry. During separate dialogues, their preferences on future developments related to mitigation in the transport and electricity sector were discussed and elicited by the method presented above. Chapter 4 gives a detailed account of the parsimonious narratives for likely and desirable future developments as perceived by the consulted civil society stakeholders. They were developed along the lines of the following six introductory discussion questions: Is an increase of total freight transport unavoidable? Is multi-modality a viable option for decarbonizing the passenger transport sector? Which alternative low-carbon fuels ought to be dominant in the future? Are landscape externalities of renewable electricity generation capacities and transmission lines problematic and what are potential remedies? Which energy efficiency growth rate is feasible and what is the role of the rebound effect? Which thermal electricity generation capacities (i.e. conventional power plants) are acceptable in the next decades? The parsimonious narratives were translated to input parameter configurations for the hybrid energy-economy model REMIND-D. Three scenarios were defined according to the criteria of likeliness, desirability with consent and desirability with dissent. In line with the German Government’s mitigation targets, all scenarios are subject to a carbon budget constraint that leads to a CO_2 emission reduction of 85% in 2050 relative to 1990. The 'continuation' scenario enforces a set of parsimonious narratives in the transport and electricity sector that are deemed likely by civil society stakeholders. The 'paradigm shift' scenario reproduces a set of parsimonious narratives perceived as desirable by the majority of civil society stakeholders. A variant of the latter, the 'paradigm shift+' scenario, additionally allows for the deployment of several technological mitigation options which the stakeholders judged as undesirable or discussed controversially.

The 'continuation' scenario foresees a dominance of motorized individual transport, unabated coal electrification, moderate energy efficiency growth rates, local resistance against windmills and

transmission lines that translate into moderate potentials for renewable electricity generation as well as a continuation of coupled freight transport and GDP growth rates. Coal electrification and fossil-fuel-based freight transport mileage induce 8.8 Gt CO_2 of committed emissions. This carbon lock-in accounts for 55% of the total CO_2 emission budget over the time horizon of analysis from 2005 to 2050. Facing a strict carbon budget that enforces ambitious mitigation, the 'continuation' scenario constitutes a counterfactual exercise illustrating what would need to happen in the other sectors for achieving ambitious mitigation if these likely trends persisted and energy efficiency and renewable electricity generation potentials are not fully exploitable due to societal resistance. As a consequence, non-technical mitigation options slowing down economic growth are exploited by REMIND-D for meeting the CO_2 budget constraint. These include significant energy service demand reductions in passenger transportation as well as final energy demand reductions for electricity and the provision of heat. Massive state intervention would be necessary to induce behavioral changes of such magnitude, e.g. through carbon pricing policies entailing prohibitively high transport costs. In such a world, individual mobility would become a luxury good. The stakeholders assess that such policies will lack social acceptance and strongly emphasize the value of individual mobility in modern societies. Also, the required electricity and heat demand reductions are considered as politically not enforceable in reality. Several stakeholders pointed out the dangers of energy poverty if any such mitigation policy is not accompanied by effective redistribution schemes. Bound to moderate energy efficiency improvements, the 'continuation' scenario exhibits mitigation costs of 3.5 % cumulative GDP losses over the period 2005-2050 as compared to a reference case that achieves 40% CO_2 emission reduction in 2050 relative to 1990. In sum, stakeholders judged he results of this counterfactual scenario as highly problematic from a socio-political point of view. Yet they reconfirmed the likeliness of its projected developments in the freight transport and electricity sector, leading to a lock-in into current behavior and carbon-intensive infrastructure. In consequence, they conclude that, if the carbon lock-in becomes reality, ambitious mitigation targets will likely be out of reach.

The two 'paradigm shift' scenarios reproduce future developments judged as desirable by participating stakeholders. These include a decrease in total freight transport mileage, a shift in the modal split of freight transport sector from road to rail, a substantial increase of public and non-motorized transport in the modal split of passenger transportation, a widespread electrification of private transport by 2030, a phase-out of conventional coal electrification until 2020, a rapid and large-scale deployment of renewable electricity generation and transmission line capacities as well as a fourfold increase in energy efficiency growth rates. REMIND-D immediately exploits these mitigation options whereby mitigation costs decrease by more than half when compared to the 'continuation' scenario, with 1.4% of cumulative GDP losses. Yet the necessary fundamental policy changes for such a scenario are put into question by stakeholders as they doubt that sufficient collective political will can be established. Several concerns were articulated for policies that aim at inducing the structural breaks from historical trends inherent to the 'paradigm shift' scenario: The quality of public transport services needs to increase significantly, both in urban environments and in rural areas. Inter alia, this would require a redirection of infrastructure investments from road to rail, an issue considered long overdue by the CSO stakeholders. Furthermore, the projected rapid decommissioning of existing coal power plants may entail increasing regional unemployment rates in Germany's structurally weak lignite mining areas. Finally, a fast

deployment of renewable electricity generation and transmission line capacities requires high procedural justice throughout the planning and installation process, including institutionalized possibilities for local communities to participate, also financially. The 'paradigm shift+' scenario which additionally allows for the controversial use of the Carbon Capture and Sequestration (CCS) technology and large-scale biofuel production achieves even lower mitigation costs of 0.8%. However, civil society stakeholders remain skeptical whether these technologies are feasible in large scale, particularly due to social refusal. They argue that the incremental effect on decreasing mitigation costs may not outweigh the direct and indirect costs of public protest.

Even though the small sample size of civil society stakeholders engaged in this research impedes inferential conclusions on the perceptions of civil society on the German energy transition as a whole, it has demonstrated that the technological solutions to the mitigation problem proposed by the model results give rise to significant societal and political implications that deem at least as challenging as the mere engineering aspects of innovative technologies. These insights underline the importance of comprehending mitigation of energy-related CO_2 emissions as a socio-technical transition embedded in a political context (Unruh, 2000). Thus, the questions of how to govern the transition and which kinds of policy instruments are suitable are equally important as the engineering-focused question of which low-carbon technologies to deploy.

6.2 Meta-Analysis of German Mitigation Scenarios for the Electricity Sector

The second part of the thesis pursues a meta-analysis of scenario projections for the electricity sector of ten mitigation scenarios drawn from six recent publications, including the ‘paradigm shift’ and ‘paradigm shift +’ scenarios developed in Chapter 4. It explores the research questions of:

- **What kinds of energy strategies for transforming the German electricity sector towards a high share of renewable electricity generation are embodied by selected mitigation scenarios for Germany? Which barriers to implementation can be identified? What are reasons for diverging scenario projections?**

Chapter 5 shows that the scenarios exploit the basic strategic options for transforming the German energy system towards a high share of renewable electricity generation (RES-E), namely increasing (i) domestic RES-E production, (ii) energy efficiency improvements and (iii) RES-E imports to a different extent and can be clustered in three groups: The first group heavily relies on exploiting energy efficiency potentials to reduce electricity demand, which is accompanied by comparatively low levels of domestic RES-E production and moderate RES-E imports. A significant barrier to implementation of such a strategy is that the exploitation of efficiency potentials cannot be steered directly and additionally energy efficiency policies may lead to unintended effects like a direct or indirect rebound. A second group of scenarios refrains from imports and balances moderate to high domestic RES-E production against high to moderate efficiency improvements. The third group puts a similar focus on domestic

RES-E production but compensates relatively higher electricity demand with substantial RES-E imports. It needs to be acknowledged that such a strategy requires an accelerated integration of European and/or Middle Eastern and Northern African electricity markets as well surplus RES-E production for export in these countries. Thus, according to the scenarios the transformation of the electricity sector towards high shares of RES-E can be attained with low, moderate or high levels of RES-E production, depending on the development of electricity demand and RES-E import potential. However, the behavioral and institutional requirements for achieving a decrease in electricity demand are not explicitly considered in most scenarios and may pose significant barriers to implementation of such a strategy. With increasingly high shares of variable electricity provision from wind and solar, both technical and institutional system integration solutions and measures need to be in place in due time. The majority of scenarios does not consider these challenges explicitly and instead maintain the assumption of sustained priority feed-in for RES-E production, which is highly doubtful from a system's perspective.

Chapter 5 further reveals that more often than not exogenous assumptions and predefined targets – instead of numerical optimization – in the modeling methodology are pivotal drivers for diverging scenario projections, particularly for the deployment pathways and feed-in of RES-E technologies. Thus, the resulting scenarios are beyond analytical traceability and constitute entirely normative scenarios that aim at delivering particular targets. Underlying input parameters are determined via expert judgments so as to achieve the targets in an optimal way. This is particularly problematic if the assumptions are not made explicit and/or are at odds with systemic effects, e.g. the assumption of sustained priority feed-in of RES-E. These insights corroborate on the one hand the necessity of improved energy system modeling tools and on the other hand the importance of taking into account the entire argumentation structure of model-based mitigation scenarios, which can be conceived as complex thought experiments of the semantic form "if → then". From this perspective, an explication of the "if" (the input assumptions) and the "→" (the energy system model) is required to attach meaning to the "then" assertion (the scenario projections). The explication of the "if" dimension refers to the techno-economic parameters as much as the implicit normative considerations.

6.3 Suggestions for Future Research

Attempting to explore how implicit normative considerations in model-based mitigation scenarios can be made explicit, this thesis revealed in an exploratory research setting that the realization of a collaborative mitigation scenario definition and evaluation process engaging German civil society stakeholders is possible in small scale and scope. Hence, the primary message for future research is that such a participatory process should be repeated in the form of a more comprehensive PEM-guided assessment of German mitigation scenarios both in terms of the scale and scope, which requires refined participatory methods so as to keep transaction costs within acceptable boundaries. Based on the findings of this thesis, the following suggests avenues for future research concentrating on three aspects that should be addressed for such an assessment: (i) refining the participatory method for realizing an assessment of mitigation scenarios in public debate that addresses normative considerations explicitly,

(ii) the scope of explored policy ends/means combinations and their direct and indirect consequences and (iii) improving the energy system modeling tools and their mode of application.

In order to refine the participatory method for realizing a more comprehensive assessment of mitigation scenarios in public debate that addresses normative considerations explicitly, one needs to address the three basic questions of "who, why and how?", i.e. whom to include in the discourse, for what reasons and by which methods and instruments, more conscientiously. For doing so, it is highly commendable to draw on the body of literature developed in the field of governance, and particularly in the field of inclusive risk governance. In general, governance analyzes the structures and processes for collective decision making involving both governmental and non-governmental actors (Nye and Donahue, 2000). Competing concepts of governance give different answers on the basic "who, why and how" questions and are essentially motivated by distinct normative models of democracy (Immergut, 2011). Risk governance is an established scientific discipline that deals with collective decision making processes for assessing and handling risks to human health and the environment. Inclusive approaches to risk governance spell out elaborated concepts on whom to include in the assessment, for what rationale and with what instruments, thereby explicitly considering the normative dimension inherent to choosing a particular governance approach as well as the value judgments inherent to making a decision in the process (Renn, 2008; Renn and Walker, 2008; Renn and Schweizer, 2009). The aim of this research avenue would be to adapt the elaborated methods developed in inclusive risk governance to the assessment process of mitigation scenarios for Germany. Also, it would be of pivotal importance that the German policymaker legitimizes the process and gives a credible commitment to implementing the commendable policy options that emerge from the assessment.

Regarding the number of policy ends/means combinations and the variety of their direct and indirect consequences explored in future assessments of mitigation scenarios it is commendable to enlarge the scope in both respects. This research considered a single mitigation target of 85% CO_2 emission reduction in 2050 relative to 1990. Future research should also critically reconsider the feasibility of this target in view of the consequences arising from policy means that are required for its attainment and explore alternative policy targets in a comparative manner. The exploration of direct and indirect consequences should be pursued in greater depth and breadth and explicitly include institutional consequences arising from conceivable governance structures, policy instruments and market designs and investment incentives required to implement the technical mitigation options considered in energy system models. For accommodating such a diverse set of mechanisms within the formal energy system modeling approach, it deems necessary to improve the process and method for developing rigorous translation rules from "model parameters" to "real-world implications".

Finally, for future assessments of mitigation scenarios, the energy system modeling tools and their mode of application should be improved. The spatial, temporal and sectorial resolution of energy system models needs to increase for considering system integration measures for variable renewables, infrastructure requirements, and the trade-offs between technological mitigation options in different sectors of the energy system in an integrated manner. Instead of employing only one energy system model, it is commendable to perform a model comparison exercise embedded in the assessment process to improve the robustness of model results. The idea is to have several energy system models

calculating scenarios with the same set of input assumptions, as for example in the ADAM (Edenhofer et al., 2010) or RECIPE project (Luderer et al., 2011). This allows for determining the bias introduced by the specific choice of modeling methods on scenario projections in terms of which scenario results are independent of the employed model and its specific assumption. Furthermore, the assumptions should be varied from worst-case to best-case to determine a robust corridor of possible mitigation pathways.

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Statement of Contribution

The chapters of this thesis are written by the author of this thesis in collaboration with her advisers Prof. Dr. Ottmar Edenhofer and Dr. Brigitte Knopf. The model development of REMIND-D was supervised by Dr. Nico Bauer. The author of the thesis has made significant contributions to all chapters from conceptual design, to technical development, numerical implementation and writing. This section details the contribution of the author to the four core chapters of this thesis and acknowledges major contributions of others.

Chapter 2

The author was responsible for the conceptual design, handling and writing of the article. Brigitte Knopf made important contributions to the structure of the article and edited the manuscript in several iterations. Meike Fink contributed to the initial outline and the comparison section. Stéphane LaBranche provided advice and proofread the article.

Chapter 3

The author was responsible for the conceptual design, handling and writing of the article. Also, the author collected all data and literature and was responsible for the numerical implementation of the model REMIND-D. The original source code of REMIND-G was provided by the Potsdam Institute for Climate Impact Research; however, the author adapted the code and calibrated the model so as to represent the Federal Republic of Germany. Nico Bauer gave continuous support in all stages of this process and supervised the development of the model REMIND-D. Brigitte Knopf contributed in extensive discussions on the model results.

Chapter 4

The author was responsible for the conceptual design, handling and writing of the article. Also, the author was responsible for the technical implementation of the scenarios and the development of the model results. The article was developed in close cooperation with Brigitte Knopf who contributed through extensive discussion in all stages of the research, including the conceptual design, and edited the article several times.

Chapter 5

The author was responsible for handling and writing of the article. The research question, conceptual design and interpretations were developed in close collaboration with Michael Pahle and Brigitte Knopf. The author was responsible for retrieving the data and generating the graphs, figures and tables.

Tools and Resources

This thesis relies on numerical modeling. Naturally, a number of software tools were used to create and run the models, and to process, analyze and visualize the results. This section lists these tools.

Modeling: All model experiments performed by the author made use of the General Algebraic Modeling System (GAMS), version 22.7.2 (Brooke et al., 1988) and the CONOPT3 solver, version 3.14S, for non-linear programs (Drud, 1994).

Data Processing: Model output was analyzed using The MathWorks' MATLAB, version 6.5 release 13 (MATLAB, 1998), Microsoft Excel, version 2003 and 2010, and Microsoft PowerPoint, version 2003 and 2010.

Typesetting: This document was prepared using LATEX2ε (Lamport, 1994), particularly the pdfpages package (Matthias, 2006), to include Chapters 2 to 5 in their given layouts. Chapter 1, 5 and 6 wre written with Microsoft Word 2010. Chapter 2 was written with Microsoft Word 2003. Chapters 3 and 4 were written with LATEX2ε (Lamport, 1994).

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