European and German low-carbon energy transition

Model-based identification of no-regret options under different types of uncertainty

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Abstract

This dissertation details possible pathways for the European and German energy transition. The open source Global Energy System Model (GENeSYS-MOD) is applied, a multi-sectoral long-term energy system model, to apply different methodologies accounting for uncertainty in the future energy system. With the goal of outlining challenges and opportunities of the energy system transformation, this dissertation provides common findings and no-regret options found across multiple studies.

Part I of this dissertation focuses on decarbonization pathways and 100% renewable energy systems in Europe. Numerous energy system models are being used, raising the need to adequately assess their results if policy and decision makers should take well-informed decisions. The first chapter draws from previous experience of modeling 100% renewable energy systems and outlines lessons learned from these exercises. Various energy transition pathways are then analyzed and common findings are synthesized which are compared to the efforts of the European Green Deal (EGD). Thereafter, the effects that short sighted decision making could have on the energy system, especially regarding the problem of stranded assets. Key findings of this part highlight the need for open science and clear result communication.

In Part II, challenges and opportunities for the German *Energiewende* are discussed. It starts by providing a comparison of five different energy system models and analyzes the impact of Germany's 2030 climate targets on the power system. The following two Chapters explore the effects of key drivers and influential factors on the German energy transition and transportation transition, in particular. Parametric sensitivity analysis is performed, highlighting areas with high impact which policy makers should focus on. It can be shown that demand reductions, next to costs of renewables and carbon prices, have the highest effect on multiple indicators relevant to the success of the energy transition.

Across all chapters of this dissertation, different methodologies to account for various types of uncertainty are applied. The results showcase that, despite uncertain future developments, common findings can be found and no-regret options formulated. In doing so, this dissertation contributes to the ongoing scientific and public debate by showcasing possible pathways, chances, and barriers of the European and German energy transition. In addition, the principles of open science are followed, allowing other researchers or practitioners to validate the findings and use the applied methodologies.

Keywords: Energy system modeling, decarbonization pathways, energy system transformation, energy policy, uncertainty, renewable energy, mobility transition

Zusammenfassung

In dieser Dissertation werden mögliche Pfadverläufe für die europäische und deutsche Energiewende beschrieben. Das quelloffene *Global Energy System Model (GENeSYS-MOD)*, ein multisektorales Langfrist-Energiesystemmodell, wird eingesetzt, um verschiedene Methoden zur Berücksichtigung von Unsicherheiten im zukünftigen Energiesystem anzuwenden. Mit dem Ziel, die Herausforderungen und Chancen der Energiewende zu skizzieren, leitet diese Dissertation gemeinsame Erkenntnisse aus mehreren Studien ab.

Teil I dieser Dissertation analysiert Dekarbonisierungspfade und 100% erneuerbare Energiesysteme in Europa. Eine steigende Anzahl an Energiesystemmodellen erfordert eine angemessene Bewertung ihrer Ergebnisse, wenn Politiker:innen und Entscheidungsträger:innen gut informierte Entscheidungen treffen sollen. Das erste Kapitel stützt sich auf gesammelte Erfahrungen mit der Modellierung von 100% erneuerbaren Energiesystemen und umreißt die Lehren, die aus diesen Analysen gezogen wurden. Gemeinsame Erkenntnisse aus verschiedene Energiewendepfade werden zusammengefasst, die mit den Bemühungen des *European Green Deal (EGD)* verglichen werden. Danach werden die Auswirkungen kurzsichtiger Entscheidungsfindung auf das Energiesystem, insbesondere im Hinblick auf das Problem der *stranded-assets*, dargestellt. Die Ergebnisse dieses Teils unterstreichen die Notwendigkeit klarer Ergebniskommunikation und einer offenen Wissenschaft.

In Teil II werden Herausforderungen und Chancen für die deutsche Energiewende diskutiert. Fünf verschiedenen Energiesystemmodelle werden verglichen und die Auswirkungen der 2030 Klimaziele auf das Stromsystem analysiert. Anschließend werden die Auswirkungen der wichtigsten Treiber und Einflussfaktoren auf die deutsche Energiewende und insbesondere die Verkehrswende untersucht. Es wird eine parametrische Sensitivitätsanalyse durchgeführt, die Bereiche mit hohen Auswirkungen hervorhebt, auf die sich politische Entscheidungsträger:innen konzentrieren sollten. Es zeigt sich, dass Nachfragereduzierungen, neben den Kosten für erneuerbare Energien und den Emissionspreisen, den größten Einfluss auf mehrere für den Erfolg der Energiewende relevante Indikatoren haben.

In allen Kapiteln dieser Dissertation werden unterschiedliche Methoden zur Berücksichtigung verschiedener Arten von Unsicherheit angewandt. Die Ergebnisse zeigen, dass trotz unsicherer zukünftiger Entwicklungen gemeinsame Erkenntnisse gefunden und *no-regret* Optionen formuliert werden können. Damit leistet diese Dissertation einen Beitrag zur laufenden wissenschaftlichen und öffentlichen Debatte, indem sie mögliche Pfade, Chancen und Barrieren der europäischen und deutschen Energiewende aufzeigt. Darüber hinaus wird den Prinzipien der offenen Wissenschaft gefolgt, die es anderen Forscher:innen ermöglicht, die Ergebnisse zu validieren und die angewandten Methoden zu nutzen.

Schlüsselwörter: Energiesystemmodellierung, Dekarbonisierungspfade, Transformation des Energiesystems, Energiepolitik, Unsicherheit, erneuerbare Energien, Verkehrswende

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In other times, I would use this occasion to thank the two people I spent time with everyday in the same office, but a global pandemic resulted in us sitting for hours in discord meetings without necessarily talking to replicate the 'office atmosphere.' Thorsten Burandt and Konstantin Löffler, thank you for being my triplets and taking me back after two years of me wandering around the world. I think the way we complement each other while sharing the same values, beliefs, and interests is the foundation of everything found in this dissertation. Without you, this would not have been possible and I am looking forward to keep working with you. I also want to thank our new generation of energy system modelers, Jonathan Hanto, Philipp Herpich, and Nikita Moskalenko who brought fresh air into our team while enduring my taste of music which, at times, is questionable, to say the least.

A major reason for my decision to return to the workgroup after having escaped for two years are the people involved. Despite working from home and having less in person contact, I always felt as part of something bigger and look forward to more in person meetings around the coffee machine. Getting along with colleagues is great but becoming best friends with them is even Greta. I specifically want to thank Lukas, Elmar, Sandra, Nina, and Richard who support my teaching efforts so thoroughly that I feel they would also manage without me.

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Thank you!

Rechtliche Erklärung

Hiermit versichere ich, dass ich die vorliegende Dissertation selbstständig und ohne unzulässige Hilfsmittel verfasst habe. Die verwendeten Quellen sind vollständig im Literaturverzeichnis angegeben. Die Arbeit wurde noch keiner Prüfungsbehörde in gleicher oder ähnlicher Form vorgelegt.

Karlo Hainsch
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List of Abbreviations

API	application programming interface.
BAU	business as usual.
BEV	battery-electric vehicle.
C2D	charge-to-discharge.
C&I	construction and investment.
CCTS	carbon capture, transport, and storage.
CGE	computable general equilibrium.
CHP	combined heat and power.
CO_2	carbon dioxide.
COP	Conference of the Parties.
DAC	direct air capture.
DG ENER	European Commission Directorate-General for Energy.
E2P	energy-to-power.
EC	European Commission.
ECEMP	Energy Climate + Energy Modeling Platform.
ECF	European Climate Foundation.
EEA	European Environmental Agency.
EGD	European Green Deal.
EIA	U.S. Energy Information Administration.
EMF	Energy Modeling Forum.
ETS	emission trading system.
EU	European Union.
FCEV	fuel-cell electric vehicle.
GAMS	General Algebraic Modeling System.
GDP	gross domestic product.
GENESYS-2	Genetic Optimisation of a European Energy Supply System.
GENeSYS-MOD	Global Energy System Model.
GHG	greenhouse gas.
GW	gigawatt.

H_2	hydrogen.
HVDC	high voltage direct current.
IAM	integrated assessment models.
IEA	International Energy Agency.
IIASA	International Institute for Applied Systems Analysis.
IPCC	Intergovernmental Panel on Climate Change.
JRC	Joint Research Centre.
KPI	key performance indicator.
LOPF	linear optimal power flow.
LP	linear program.
MILP	mixed-integer linear programm.
Mt	megaton.
NDC	nationally determined contribution.
NET	negative emission technology.
O&M	operation and maintenance.
OECD	Organization for Economic Co-operation and Development.
oedatamodel	Open Energy Datamodel.
oemof	Open Energy Modelling Framework.
OEP	Open Energy Platform.
openENTRANCE	**open** **EN**ergy **TR**ansition **AN**alysis for a low-**C**arbon **E**conomy.
OS	open source.
OSeMOSYS	Open Source Energy Modelling System.
OSPSM	open source power system models.
OSS	open source software.
PHS	pumped hydro storage.
PJ	petajoule.
POL	political boundaries scenario.

PSI	Paul Scherrer Institut.
PV	photovoltaics.
RED	reduced foresight scenario.
RES	renewable energy sources.
SA	sensitivity analysis.
SSP	shared socio-economic pathways.
TREQ	transparency, reproducibility, and quality.
TWh	terawatt hour.
UBA	German Environment Agency (*Umweltbundesamt*).
UNEP	United Nations Environment Programme.
VRE	variable renewable energy.
WEO	World Energy Outlook.
WIP	Workgroup for Infrastructure Policy.
°C	degree celsius.

Chapter 1

Introduction

1.1 Motivation

I always have been a numbers guy. During my last year of high school, I was not really sure which studies I should chose except for the fact that I wanted to go to university. Eager to get advice from outside, my math teacher convinced me to pursue a degree in mathematics since he thought I had an affinity for numbers and formulas. Unfortunately, I quickly realized during my first semester studying mathematics at the *Humbuldt Universität zu Berlin* that, apart from grades, numbers seemed to be less of a core concept in academic mathematics. In the face of at least four additional semesters of definitions, theorems, lemmas, and proofs, I opted for a change of scenery and started studying industrial engineering at the *Technische Universität Berlin*. Right away in the second semester I took a class called *Operations Research*, a term I had never heard of back than but is now the field I have the pleasure to work in every day.

During my studies at university and occupation at the *Workgroup for Infrastructure Policy (WIP)*, I grew interested in quantitative methods and transforming real world problems into mathematical formulations. Conveniently, in 2016 I attended a course called *Operations Research - Methods for Energy and Resource markets* which had the objective of creating an energy system model to analyze a pathway for a global energy system model based on 100% renewables. The course was led by Professors Christian von Hirschhausen and Pao-Yu Oei and is also the place where I met my future colleagues Thorsten Burandt and Konstantin Löffler. In a group of 20 students, we developed an energy system model based on the Open Source Energy Modelling System (OSeMOSYS) which, after some additional tweaks and improvements, became the Global Energy System Model (GENeSYS-MOD) and was published a year later (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017).

Over the course of the following years, I was intrigued by the possibilities the model we developed provided and my interest in numbers and formulas my math teacher attested flourished. After a compelling stay at the *Paul Scherrer Institut (PSI)* in Switzerland under the supervision of Vangelis Panos, I decided to continue working in the field of energy system modeling and pursue the completion of the dissertation presented here. Reuniting with my former colleagues, I resumed my work with GENeSYS-MOD with the goal of expanding its functionalities and applying it to analyze decarbonization pathways for the energy system.

A fact I learned quickly, however, was that no matter how elaborated a model and no matter how well founded the data is, model results always have their weak points and basically never predict the future accurately. While the former shortcoming can be tackled by continued improvement of the model formulation and the inclusion of new features, the latter is less straightforward to approach. How can someone assess the quality of model results, if they almost certainly will differ from actual future developments? And if I can't answer this question for my very own model, how should others be in the position to do so without having all the background information accessible to me?

The solution to this problem, I concluded, could be found in my own approach towards the methods I applied and their communication. Models in general, no matter the application, will be unable to 100% accurately predict the future and are thus surrounded by various degrees of uncertainty. An everyday example is the weather forecast. If one focuses on the pure numbers, one might say that the forecast was wrong if it predicts 28 degree celsius (°C) for the following day but the actual temperature ends up being 29°C. But if the trend is being analyzed, lets say the forecast predicts higher temperatures than today where it has 25°C, then the forecast is correct. This simplified example serves to illustrate that, to paraphrase George E. P. Box, *models might be wrong but can still be useful* (Box 1976). By carefully addressing what can be concluded from model results and what can not, modelers are able to provide well founded information for policy and decision makers. This task naturally falls into the responsibility of the modeler, since he or she is the only one who has an overview over all made assumptions and applied methodologies.

With the need for rapid action in the energy system, caused by global warming and the necessity to stop it (IPCC 2013, 2014a), policy and decision makers rely on analyses and findings from researchers and practitioners from all fields to support their decisions. GENeSYS-MOD is a tool which can help to shed light on future developments of energy transition[1] pathways and, in addition, is fully open source providing the necessary information about and access to the model and its applications. Therefore, in this dissertation, I use GENeSYS-MOD with different methodological approaches to address the following research questions:

1. How can lessons learned from best-practices in energy system modeling be used to communicate results and provide advice to policy makers?
2. What challenges arise for the European and German energy system transformation and which areas are of specific interest for policy makers?

[1] Throughout this dissertation, the terms transition and transformation will frequently be used. I hereby adhere to the definition of Child and Breyer (2017), which describe transformation as change in physical aspects of energy systems (e.g., "the transformation of the energy system", referring to the technological changes required), while transition describes change across the entire socio-technical system (e.g., "the energy transition", encompassing also the changes in social structures, behavior, or political thinking).

3. Which methods can be used to deal with uncertainty in energy system modeling and which conclusions can be drawn from model calculations despite this uncertainty?

The remainder of this introduction continues with an overview of the current situation of the energy system and climate policies in the European Union (EU) and Germany. The field of energy system modeling is outlined by categorizing the different approaches of models and uncertainty consideration, with GENeSYS-MOD being one example. I then proceed to describe the individual chapters of this dissertation and also highlight my own contributions to their pre-publications. Lastly, I conclude by formulating common findings addressing the previously formulated research questions and point out areas for possible future research.

1.2 The state of the European and German energy system and climate policy

1.2.1 History and current situation of European climate policy

Climate policy became an area of focus around the 1990s in Europe, shortly after the first report by the IPCC and WMO (1992) and WBGU (2011). The initial goal was to keep greenhouse gas (GHG) emissions around 1990 levels by 2000, as well as focusing on the promotion of renewable energies and energy efficiency improvements. Later that decade, in 1996, the European Community for the first time established a long-term climate goal, aiming to keep global warming below 2°C compared to pre-industrial levels. Through a "burden sharing" agreement, national targets for all 15 member states were implemented to achieve said goal. A year later, the climate summit in Kyoto saw a European commitment to further reduce GHG emissions by 8% between 2008 and 2012. The expansion of the EU did not impede these targets, as almost all new member states declared their own GHG emission reduction targets as a result of the Kyoto Protocol.

To further stimulate global ambitions, in 2007 the "20-20-20 by 2020" strategy was adopted, aiming for: (i) a 20% reduction of GHG emissions by 2020 compared to 1990, (ii) 20% renewable energies in final energy consumption, and (iii) a 20% reduction in EU-wide final energy consumption. Two years later, the "Climate and Energy Package" was implemented which among other things introduced a directive on emission trading and effort-sharing. Electricity generation and industrial processes were now covered by an emission trading system (ETS) on European level, with emission reduction targets being defined for emissions from both, the ETS sector and non-ETS sectors on a national level. Also in 2009, the commitment to the 2°C target was renewed with adding an emission reduction target of 80-95% for 2050 compared to 1990 levels.

A historic breakthrough in international climate policy happened in 2015 at the 21st Conference of the Parties (COP) in Paris, where 195 countries agreed to limit global warming to well below 2°C and aiming to achieve 1.5°C compared to pre-industrial levels (UNFCCC 2015b). The agreement was ratified by the EU in 2016. Since then, various directives, programs and packages have been developed and implemented to achieve the ambitious goals. Examples are the "A clean planet for all" strategic long-term vision (European Commission 2018a), the European Green Deal (EGD) in 2019 together with the pledge for climate neutrality by 2050 (European Commission 2019b), the European Climate Law which increased the 2030 climate targets (European Parliament and Council of the European Union 2021), and subsequently the "Fit for 55" package (European Council 2022a) detailing how to achieve them.

However and despite all of the mentioned measures, the EU will faces many challenges in the upcoming years if the climate targets are to be achieved. According to the European Environmental Agency (EEA), emissions in 2020 were 31% below 1990 levels, although some of this effect is strongly related to the COVID-19 pandemic (EEA 2021). They also conclude that additional efforts are required in many areas (i.e., emissions, primary and final energy consumption, as well as renewable energy share), since current projections suggest that the climate targets will be missed. Naturally, not all member states face the same challenges and, therefore, it is easier for some to be in line with the set targets than for others. Figure 1.1 details which member states complied with which EU-wide climate targets in 2020. Since these targets are EU-wide, country particularities play a significant role with respect to the success of the implementation and the fact that a country reached certain targets does not necessarily correlate to their efforts in recent years. The figure also highlights that energy supply remains the sector with the highest amounts of GHG emissions, although transportation and industry are closely behind (EEA 2021). The latter two sectors are significantly more difficult to decarbonize, however, which is also illustrated by the fact that emissions in the transportation sector increased since 1990 if international aviation and maritime transportation are considered (European Commission. Directorate General for Mobility and Transport. 2021).

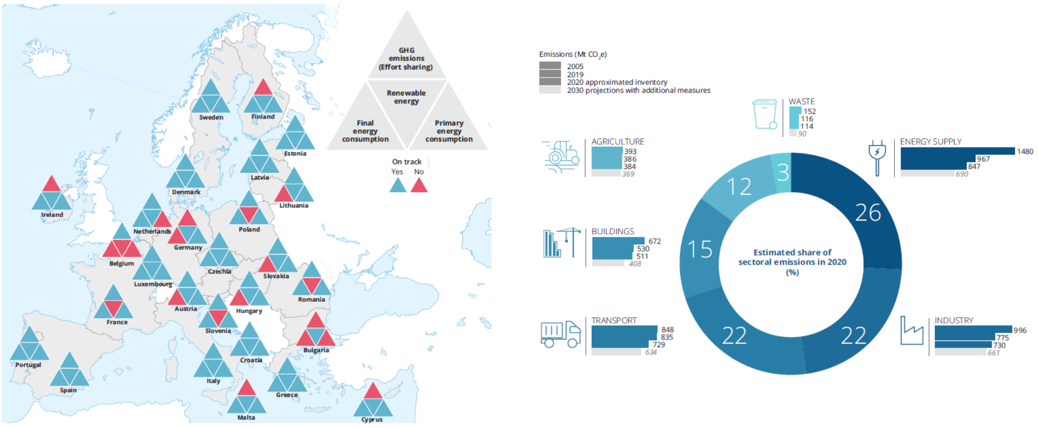

Figure 1.1: Member state's progress towards the 2020 climate targets (left) and EU-wide sectoral emissions and projections (right). Source: EEA (2021)

1.2.2 German climate policy and state of the energy system

Germany, being the member state of the EU with the largest population and economy, faces unique challenges if the target of zero emissions and no nuclear power in 2050 is to be achieved. Out of all European member states, Germany emits by far the most GHG emissions, more than doubling the amount of the second highest country, that being Poland (EUROSTAT 2022b). The energy system historically developed a high reliance on coal and lignite but also fossil fossil gas and oil are still relevant in multiple sectors. As a result, many iterations of policies aiming at reducing GHG emissions and limiting global warming were implemented over the past decades.

After the German Federal Court deemed the previous targets too low, the German parliament decided on an update of the existing climate policies in 2021, increasing the GHG emission reduction targets to -65% in 2030, 88% in 2040 (both compared to 1990 levels), and zero emissions in 2045 (BMWK 2022a). Furthermore, sectoral emission reduction targets were tightened, detailing the contribution each sector would have to make. The in autumn 2021 newly elected government doubled down on these targets. For the electricity sector, 80% renewable energies are planned until 2030 to, on the one hand, reduce emissions from power generation and, on the other hand, facilitate the electrification of other energy sectors. Table 1.1 details selected climate and energy goals for Germany, as well as the current progress towards them and required effort. Yet, even though emissions decreased by more than 35% between 1990 and 2019 and even though climate targets were updated, studies point out that it seems unlikely that Germany can achieve its climate goals (BMU 2021b; Agora Energiewende 2022). According to BMU (2021b), GHG emission reduction targets and renewable energy share in electricity production miss the important milestones in 2030,

Table 1.1: Overview of selected climate and energy goals in Germany, current situation and progress towards their achievements.

Category	Goal (2030)	Currently (2021)	Current p.a. change (since year)	Required p.a. change (2022-2030)
GHG Emission (Umweltbundesamt 2022e, 2022f)				
Total	438 Mt	762 Mt	-15 Mt (1990)	-36 Mt
Energy	108 Mt	247 Mt	-7 Mt (1990)	-15 Mt
Industry	118 Mt	181 Mt	-3.3 Mt (1990)	-7 Mt
Buildings	67 Mt	115 Mt	-3.1 Mt (1990)	-5.3 Mt
Transportation	85 Mt	148 Mt	-0.48 Mt (1990)	-7 Mt
Renewable Energies (BMWK 2022b; McKinsey 2022)				
Share in electricity generation	80%	42%	+2.3% (2010)	+4.2%
Wind Onshore Capacity	100 GW	56 GW	+2.7 GW (2010)	+4.8 GW
PV Capacity	200 GW	59 GW	+2.7 GW (2010)	+7.4 GW
Other (McKinsey 2022; Kraftfahrtbundesamt 2022; tagesschau.de 2022)				
Electric Vehicles	15 million	310,000	+ 309,000 (2021)	+1,633,333
Heat pumps	4.1 - 6 million	1 million	+ 158,000 (2021)	+340,000-500,000

2040, and 2050 following the current trajectory. Additionally, Agora Energiewende (2022) points out that Germany reaching its 2020 climate goals was caused by the Covid pandemic and resulting energy demand reductions, with emissions in 2021 missing the mark. Therefore, the following sections briefly outline the role of different energy carriers and sectors in the German energy system, highlighting their particular challenges and opportunities.

1.2.2.1 Energy carriers and sources

Hard coal and lignite

Hard coal and lignite were for many years the backbone of the German energy system. Both are domestically available and while mining of hard coal was stopped in 2018, 126 million tons of lignite were still being extracted in 2021 (Statistik der Kohlewirtschaft e.V. 2022). Overall, more than 2,000 petajoule (PJ) of energy were produced by coal in Germany in that year (Umweltbundesamt 2022c), accounting for almost 20% of primary energy. Hard coal and lignite are used in all sectors, either directly or indirectly through the use of electricity. In 2021, 30% of electricity, the equivalent of 156 terawatt hours (TWH), was produced by hard coal and lignite (Statistisches Bundesamt 2022b), part of which originates from combined heat and power (CHP) plants which produced about 20 TWh of heat used in the buildings sector in 2020 (AG Energiebilanzen e.V. 2021). The remaining applications focus on the industry sector, where process heat of around 90 TWh is generated for industrial processes requiring high temperature heat (Umweltbundesamt 2022a).

To reduce the reliance on coal as well as GHG emissions, a Coal Commission was formed to elaborate a plan on a step-wise reduction of coal usage in electricity production as well as recommendations on how to support regions with high socio-economic reliance on coal. As a result, a coal phase-out date was set to 2038, which was adjusted by the new German government aiming now at 2030. To put the required effort into perspective, electricity generation power by hard coal and lignite decreased by 37% between 2010 and 2019 (AG Energiebilanzen e.V. 2021). To achieve the goal in 2030, roughly twice the speed than in the previous decade is necessary. With the high importance of coal in the energy system, facilitating the phase-out of capacities while considering socio-economic impacts will be a key challenge within the next decade.

Fossil gas

Similar to coal, the use of fossil gas is spread across multiple sectors of the energy system. More than 3,000 PJ (roughly 27% of primary energy) of fossil gas were used in 2021, mostly for space heating and in industry (Umweltbundesamt 2022a, 2022c). However, while coal consumption was significantly reduced between 1990 and 2021, fossil gas consumption increased by almost 50% (Umweltbundesamt 2022c). Most of the fossil gas consumed in Germany is imported, since only around 5% of total consumption is produced domestically (BP 2022). More than 50% of imports stem from Russia, with Norway and the Netherlands being the remaining significant suppliers (BP 2022).

The use of fossil gas in the energy system is increasingly being questioned, and with good reason. With methane having a 87 times higher 20-year global warming potential than CO_2 (Hirschhausen, Kemfert, and Praeger 2022; IPCC 2014b), leakage during extraction, transportation, storage, and consumption has tremendous effects on global warming. Furthermore, the high import-dependency can lead to unfavourable developments, as can be observed right now where, as a consequence of the Russian invasion of Ukraine, gas supply decreases while prices increase significantly. As a result, EU member states agreed on a voluntary reduction of gas demand by 15% this winter (European Council 2022b). Additionally, the target to phase out gas imports from Russia in the medium term was formulated, a monumental task considering that more than 50% of gas imports into the EU originate from Russia (EUROSTAT 2022a).

Oil

Oil is the most used energy carrier in the German energy system, where more than 3,8000 PJ are mainly being used in the transportation sector and, to some degree, in the heating sector

(Umweltbundesamt 2022a, 2022c). In the transportation sector, oil and its derivatives are required as fuel for various modes of transportation, with road transportation dominating by far. Similar to the case of fossil gas, Germany heavily relies on imports of oil which accumulated to 36 million tons in 2021 (Statista 2022c). The effects of the Russian invasion were also felt with respect to oil prices, with the consumer diesel price surpassing the mark of 2€ per litre for the first time in history in spring 2022. Furthermore, the drought in the summer of 2022 lead to ships carrying oil barrels having to be loaded partially, resulting in higher prices at the gas stations (Reuters 2022). Substituting oil consuming vehicles and moving towards alternative power trains (e.g., electric) will be key to reduce oil consumption and meet the GHG emission reduction targets, especially in the transportation sector.

Nuclear

After the tsunami and subsequent melt-down of the nuclear power plant in Fukushima in 2011, Germany decided to phase-out all nuclear power plants until 2022. Consequently, the three nuclear power plants which remain operational at the time of writing are planned to be shut down by the end of the year. As a result, the focus is set on decommissioning of power plants and the disposal of radioactive waste (BGE 2020). Nuclear power was responsible for about 65 TWh in 2021, a level similar to the one of fossil gas (Statistisches Bundesamt 2022b). With the planned end of commercial nuclear power at the end of 2022, the role of nuclear power will disappear in the upcoming years, despite a current debate on possible operational extensions as a reaction to increasing gas prices and concerns about security of supply due to the Russian invasion of Ukraine (BMUV 2022).

Renewables

Renewable energies are the oldest form of energy generation, with waterwheels already being used more than 2,000 years ago. Nowadays, their importance is on the rise again fueled by growing concerns about climate impacts of fossil fuel combustion. In Germany, more than 15% of primary energy consumption came from renewable energies in 2021 (Umweltbundesamt 2022c), most of which is used for power generation with about 220 TWh (Statistisches Bundesamt 2022b). With the ambitious goals set by the EU and Germany as one of its member states, renewable energies will become the backbone of the energy system with the question about their feasibility and use-cases shifting from ”if” to ”how”.

The five main forms of renewable energies are wind, solar, hydro, geothermal, and bio energy. Wind turbines can be placed on- and offshore, with offshore installations typically benefiting from higher capacity factors and, thus, higher generation but at the expense of higher installation costs and infrastructure requirements. With around 111 TWh in 2021, more than half of Germany's renewable electricity generation is produced by wind turbines (Statistisches Bundesamt 2022b). Solar energy is mainly being used in the form of photovoltaics (PV), contributing 45 TWh of electricity in 2021 (Statistisches Bundesamt 2022b). Apart from its usage in the electricity sector, solar energy is additionally used in the buildings sector in the form of solar-thermal installations, mainly providing hot water. Bioenergy, being the third pillar of renewable energies, is less used in the electricity sector (50 TWh in 2021) and rather provides space heating in the buildings sector (171 TWh) with some additional minor applications in the transportation sector (Umweltbundesamt 2022b). Lastly, hydropower has some limited applications in power generation but comes with the added possibility of assisting with electricity storage in the form of pumped hydro storage (PHS). According to the Bundesnetzagentur (2022), almost 10 gigawatt (GW) of PHS are installed in Germany, with limited potential for expansion.

For a successful implementation of an energy system relying to 100% on renewable energies, the existing capacities will have to be expanded rapidly. However, in some cases the presence of incumbent actors slows down the necessary installations. As an example, the federal state of Bavaria implemented a minimum distance of wind turbines to the next settlement of at least ten times the installation's height, drastically slowing down the expansion of wind power in the largest federal state. In addition, a successful utilization of renewable energies comes with challenges and opportunities for the different energy sectors which will briefly be highlighted in the following parts.

1.2.2.2 Energy sectors

Electricity

In general, the role of renewable energies in the electricity sector is agreed upon. With wind, PV, hydro, and bio energy all being technically and in many cases already economically feasible technologies, questions surround regional particularities as well as how to deal with large amounts of renewables. While, for example, wind power can benefit from higher capacity factors in the northern parts of Germany, as well as the North and Baltic Sea in the case of offshore wind, the southern regions favour PV due to better solar irradiation. The major point of discussion regarding renewable energies addresses the situation with low wind and PV output caused by their fluctuating nature. However, studies show that flexibility options in the form of increased interconnections, demand response, storage, and sector coupling can mitigate the negative effects as shown in a recent comprehensive review by Breyer et al. (2022).

Buildings

The German buildings sector today is mainly characterized by a dependence on fossil gas and oil for space and water heating. With both energy carriers having to be phased out in the near future to reduce emissions, questions arise about their possible replacements. Biomass is already partially being used but has limited growth potential in general due to land-use competition with agriculture. Electricity based solutions (e.g., heat pumps) could help with the energy transition in the buildings sector but require the electricity to be decarbonized in the first place. Additionally, reducing energy demand by renovating buildings and improving insulation could play a significant role (European Commission 2019a), with the renovation rate in Germany stagnating around 1% p.a. for years (Umweltbundesamt 2020c).

Industry

In the industrial sector, different industry branches have different requirements and energy demands. Energy carriers are mostly used for their energetic properties, although around 12% of energy carriers are used as feedstock, especially in the chemical industry (Statistisches Bundesamt 2021a). With fossil gas, coal, and oil all playing relevant roles in the industry's energy consumption, a replacement by renewables needs to take the particularities of the respective industry branches into account for a successful decarbonization. This is especially the case for iron and steel production, which requires high degrees of temperature which are currently difficult to obtain without fossil energy carriers, and the cement industry, where emissions occur passively during the decomposition of materials.

Transportation

Emissions in the transportation sector in Germany are currently at similar levels as in 1990 (Umweltbundesamt 2022f). The main cause is an increase in overall demand which undermines advances in energy efficiency and emission intensity. Two forms of transportation can be distinguished: passenger and freight transportation. Passenger transportation is the dominating form, both in terms of volume but also emissions, with motorized private transportation (i.e., cars) being responsible for more than 80% of passenger transportation volumes in the EU and Germany (Statistisches Bundesamt 2021b). And while technological options are already available, as is the case with battery-electric vehicles (BEVs), their deployment needs to accelerate significantly if climate targets are to be achieved. As of April 2022, almost 690,000 BEVs were registered in Germany (Kraftfahrtbundesamt 2022). If the targeted number of 15 million BEVs should be achieved by 2030, almost every second newly registered vehicles would have to be electric in Germany until then. But concerns about driving range, battery lifetime, recharging time, and availability of charging infrastructure slow down the shift towards electric mobility. Furthermore, direct electrification might not be a viable solution for freight transportation other than on rails, with other renewable energy carriers (e.g., hydrogen produced by renewable energies) having to be commercially available to fill that gap (Staffell et al. 2019). As a result, the transportation sector stands in front of a huge challenge in the next decades, which as why Chapter 7 of this dissertation particularly focuses on the upcoming transition of the transportation sector.

1.2.3 Modeling of 100% renewable scenarios for energy and climate policy

Energy system modeling has been used for many years to support policy and decision makers. The most prominent example is most likely the Intergovernmental Panel on Climate Change (IPCC) and their various assessment reports, which analyze and highlight numerous pathways compatible with various global warming targets (IPCC 2022, 2018). In these reports, results from energy system models as well as climate models are used to provide policy makers with an overview of trends, challenges, and areas of action.

With 193 parties having ratified the Paris Agreement, the responsibility falls on them to facilitate and execute the energy transition. As a result, many countries or regions rely on regional applications of energy system models to address the particular challenges within them. In the EU, the "EU Reference Scenario is one of the European Commission's key analysis tools in the areas of energy, transport and climate action [which] allows policy-makers to analyse the long-term economic, energy, climate and transport outlook" (European Commission 2020a). The modeling frameworks applied for the analysis center around the PRIMES framework, an energy system model developed by E3Modelling in Athens (E3MLab 2018). Similarly, the U.S. Energy Information Administration (EIA) applies the NEMS model for the analyses in their Annual Energy Outlooks (EIA 2022). In addition, many energy system models are developed within research projects funded by governmental institutions, which use the outcomes as information source for policy decisions but also to evaluate the allocation for future research funds.

Across all the mentioned analyses, different ways of modeling the future energy transition can be observed. On the one hand, normative model analyses depart from a state which should be achieved or is desirable (e.g., climate targets, renewable shares, etc.) and provide information on which measures and developments would be necessary to achieve the final state. On the other hand, positive studies raise assumptions on certain techno-economic and socio-political developments and aim to project how these developments would play out in the future. It is important to note that model results are no forecasts but should be used perform '*what-if*' analyses. The result is a plethora of different scenarios and pathways exemplified in Figure 1.2, illustrating global climate target compatible decarbonization scenarios and the ranges between different assumptions.

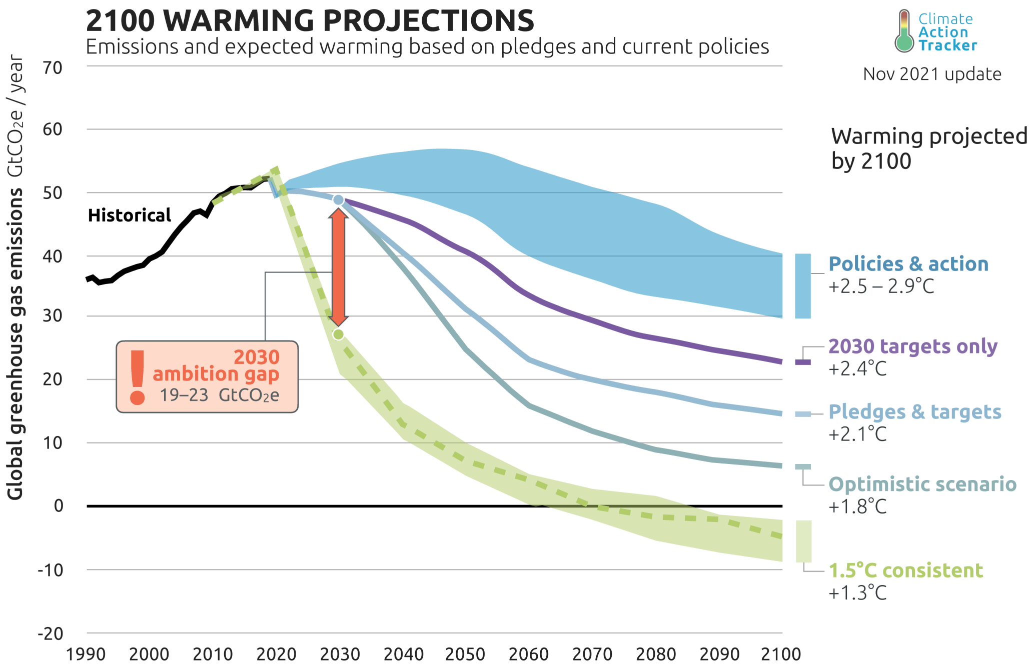

Figure 1.2: 2100 global warming projections and emission trajectories. Source: Climate Action Tracker (2021)

The Figure additionally showcases that emissions will have to be removed completely for a 1.5°C target, raising the need for GHG neutral energy generation. This can be achieved by, on the one hand, relying fully on renewable energies, as one of their main properties is that no GHG emissions are produced or, in the case of biomass, only if they were previously extracted from the atmosphere. On the other hand, removing emissions from existing processes through the use of carbon capture, transport, and storage (CCTS) as well as relying on nuclear power could facilitate the decarbonization of the energy system. However, concerns about large-scale availability of storage sites as well as questions about the effectiveness of CCTS should lead to renewable energies being preferred (Oei and Mendelevitch 2016; Minx et al. 2018). As a result, the field of modeling 100% renewable energies experienced rapid growth lately as pointed out by Breyer et al. (2022), with more than 100 peer-reviewed articles published in 2021.

Studies analyzing 100% renewable energy systems are plentiful, with the first ones dating back to the mid 70's (Sorensen 1975; Lovins and Friends of the Earth 1977). The first study analyzing a global energy system based on 100% renewables in 2050 was published 20 years later, also by Sørensen (1996). However, it took until the second decade of the 2000's for this field of research to develop. Prominent figures and studies analyzing 100% renewables are Bogdanov, Ram, et al. (2021), Jacobson, Delucchi, Bauer, et al. (2017), Mathiesen, Lund, and Karlsson (2011), Brown, Hörsch, and Schlachtberger (2018), or Teske (2019). However, in recent years the topic of 100% renewables sparked some controversy, as can be observed in the criticism of Jacobson et al. (2015) by Bistline and Blanford (2016) and Clack et al. (2017) and the subsequent rebuttal by Jacobson et al. (2016). The typical concerns are technological infeasibility, techno-economic disadvantages, or missing resources to facilitate a system based on 100% renewables. Yet, Breyer et al. (2022) argue that all of these concerns are counteracted by increasing evidence from the literature.

This fact becomes especially important when considering strengths and weaknesses of energy system model analysis. As Huntington, Weyant, and Sweeney (1982) pointed out: models should be used for insights, not numbers. Later sections of this dissertation (especially Section 1.3.2) elaborate on the concept of uncertainty in energy system modeling, yet one aspect will be discussed at this point. Energy system models, untouched by the type of model or analyses, rely on assumptions which are surrounded by uncertainty. Specific results of models (i.e., exact numbers) will most certainly be different from the actual future outcome which can be observed when taking any energy system analysis from the past and comparing it to the current situation. Nevertheless, this does not render the methodology pointless but rather shifts the focus towards the identification of common and robust insights. A rising number of studies analyzing the feasibility and configuration of energy systems based on 100% renewable energies, therefore, facilitates a better understanding of the issue and allows the formulation of robust advice for policy and decision makers. They, in turn, rely on clear and open communication of these findings as well as underlying assumptions, since they are usually no experts in the field of energy system modeling. This concept of openness on various levels can also be summarized as "open science" an deserves a brief introduction in the following section.

1.2.4 Open science

The field of open science emerged in recent years, fueled by an increasing interconnected world where access to information is provided to everyone connected to the internet. Vicente-Saez and Martinez-Fuentes (2018) define open science as "the transparent and accessible knowledge that is shared and developed through collaborative networks." While multiple different subcategories of open science exist, three are noteworthy in the field of energy system modeling. First, open source is a term originating from computer science and describes the openness of source code or other modeling tools. Second, open data refers to publicly available data which was used for the analysis with unrestricted copyright access. Third and lastly, open access mainly describes the accessibility of research papers and studies.

The benefits of following these principles are manyfold. Authors benefit from higher exposure, leading to more interactions with public groups in research field of high public engagement but also with other researchers who might share interest in the topic or work on similar ideas (Mustari 2018). The articles and work itself profit from this exchange with other parties, as methodologies can be validated and possible shortcomings or mistakes addressed quickly which was proven by Paulson, Succi, and Eberlein (2004) who showed that bugs in open source software projects were found faster than closed ones. Moreover, it becomes easier to build upon already existing work, reducing double efforts and making research more effective (Pfenninger et al. 2017).

Another key aspect of open science is the way knowledge is created and communicated (Fecher and Friesike 2014). For the field of energy system modeling, the implications are that findings need to be presented and communicated in an adequate manner. To reiterate the phrase from Huntington, Weyant, and Sweeney (1982): models generate insights, not numbers. The only ones who can accurately assess the insights gained from a model run are the modelers who set up the run themselves, since they are the only ones who (should) know all assumptions and model particularities in the case at hand. Therefore, it is their responsibility to communicate not only the findings of their study but also shortcomings and possible uncertainties of the approach chosen. If this is not considered sufficiently, readers might jump to premature conclusions and, in the case of policy and decision makers, base their actions on them which potentially have strong implications on the energy transition. However, in the case of open and clear communication the decision process can be supported by consistent and robust results which should be the aim of every researcher, no matter the field of research.

1.3 Energy system modeling and uncertainty consideration

1.3.1 Classification of energy system models

Energy system models are mathematical formulations which depict parts of or entire energy systems. As such, the energy system can be considered as a system which "[...] comprises all components related to the production, conversion, delivery, and use of energy" (Allwood et al. 2014). It is important to note that this refers to all types of energy sectors and not only electricity, which especially in the field of modeling has been a point of emphasis for many years. The system approach was first defined by Bertalanffy (1950, 1957). In contrast to traditional analyses which focus on the object being studied, the system approach focuses on the interactions between the matter being investigated and the rest of the system (Nakata, Silva, and Rodionov 2011). Therefore, energy system analysis and, subsequently, modeling highlight the interactions of all parts and players of the energy system with each other.

Naturally, many different types of energy system models have been developed over the years. The reason for this development is, mainly, twofold. On the one hand, no model in existence is capable of analyzing all aspects desired and with sufficient degree of detail, hence new models are developed to fit the specific needs of the developers. As described in the previous paragraph, the system school of thinking originated from the desire to analyze a wider range of interactions between different components within such a system. Similarly, energy system model's development can be seen as the desire of modelers to understand the interactions between many energy sectors, contrary to a focus on a single sector (e.g., electricity). On the other hand, new models might be developed because the accessibility of already existing models, despite them being suitable for the analysis at hand, is insufficient. If entry barriers are set too high for new modelers to use a model, be it due to a lack of documentation or access restrictions, new models have to be created out of a necessity. The result of both reasons is that numerous energy system models with different approaches, strengths, weaknesses, and possible use-cases exist, raising the need of understanding these differences in order to chose the correct model for the correct application.

Over the past decades, numerous classifications of energy system models were conducted (Prina et al. 2020). Already in 1993, Grubb et al. (1993) distinguish models between their approach, time horizon, and sectoral coverage. Others like Hourcade et al. (2006) detail the additional need of bridging the gap between top-down and bottom-up models while Cao et al. (2016) argue for considering the openness and accessibility of models. Building on all of the mentioned studies, Prina et al. (2020) provides a classification of energy system models based on four criteria: (i) bottom-up vs. top-down, (ii) foresight approach, (iii) resolution, and (iv) transparency.

Top-down energy models describe the economy as a whole by taking an aggregated view of the energy sector and the economy, simulating economic development in terms of energy demand, supply, and employment (Herbst et al. 2012). They, therefore, aim at connecting the energy system to macro-economic sectors (Prina et al. 2020). By adopting this perspective, technological detail is sacrificed for a better representation of economic sectors and generated welfare. Typical examples of top-down models are input-output models, econometric models, system dynamics, and finally computable general equilibrium (CGE) models (Herbst et al. 2012). In contrast, bottom-up models focus on high technological degree of detail to describe present and future energy supply and demand. They complement top-down models in a sense that weaknesses of top-down models (i.e., techno-economic representation) is the strength of bottom-up models and vice-versa. Optimization models, simulation models, and multi-agent models can all be considered bottom-up models and differ in their mathematical approach. The model used for the analyses in this dissertation, GENeSYS-MOD, can also be classified as a bottom-up model and, thus, the remaining categorizations will focus on this type of models. Lastly, partial equilibrium models can also be classified as bottom-up models and serve as the bridge described by Hourcade et al. (2006), since they contain aspects of equilibrium models as well as optimization models.

The foresight approach describes the way the optimization model deals with multiple time periods. As will be explained in more detail in Section 1.3.2.2 of this dissertation, most energy system models adopt the perspective of an all-knowing central planner, which has knowledge about all future developments as well as about the effect of decisions on all following periods. However, some models follow a different approach in which model periods are calculated without considering long-term consequences of decisions. While some models adopt the latter approach of limited, or myopic, foresight to analyze and compare the results with those of perfect foresight, others do it out of necessity since it reduces computational complexity significantly. Both, reduced and perfect foresight models have their benefits which makes it imperative to correctly assess and interpret model results.

Different dimensions of resolution exist in energy system models. Most energy system models are flexible frameworks with their temporal and regional resolution depending on the provided data. In other words, they can be applied to any given region as long as techno-economic data is provided on the same level of regional (dis)aggregation. However, sectoral resolution might not always be totally flexible, as some of the interactions within one or between multiple sectors might be unique to them. Some models focus on single sectors allowing a high degree of detail (e.g., traditionally the electricity sector), while others explicitly focus on the interactions between many sectors (e.g., electricity, buildings, industry, and transportation). Furthermore, the degree of detail with which technologies are modeled can differ from model to model. It is important to understand that all dimensions of resolution compete for the same amount of computational resources, meaning that an increase of one dimension typically requires a reduction of another. Prina et al. (2020) showcase this effect where they highlight the degree of different resolutions across multiple energy system models, highlighting that no model excels in all dimensions.

The final criteria which can be applied to classify energy system models is their transparency. As argued by Pfenninger et al. (2017), the in Section 1.2.4 described concept of open science also applies to energy system models with openness of model and data being important, since they lead to higher quality science, greater productivity by reducing duplicated efforts, and a more effective science-policy boundary. However, many energy system models lack in one or more aspects regarding open science as shown by Prina et al. (2020). Reasons for that could be ethical or security concerns in the case of data, creating unwanted exposure, time constraints, or institutional and personal inertia (Pfenninger et al. 2017). Opening energy system models requires a substantial amount of effort put into documentation and communication. This additional effort might not perceived to be worth by modelers if the benefit does not outweigh the costs. However, as argued by many researchers (Pfenninger et al. 2017; Prina et al. 2020; Brown 2020; Huppmann et al. 2022; Hilpert et al. 2018), energy system models should follow the open science principles in order to validate model results and improve the overall quality of science.

1.3.2 Accounting for uncertainty in energy system modeling

The concept of uncertainty is not new, with multiple seemingly similar definitions of the term being used in the literature. For example, Milliken (1987) summarizes that the three most common definitions of, in this case, ”environmental uncertainty” are: (1) an inability to assign probabilities as to the likelihood of future events, (2) a lack of information about cause-effect relationships, and/or (3) an inability to predict accurately what the outcomes of a decision might be. Following his definition, in this dissertation uncertainty will be defined ”[...] as an individual’s perceived inability to predict something accurately”´(Milliken 1987, 136). This inability to predict something can be applied both for the future but also for the present, as uncertainty can also be reflected in not knowing exactly how the current state looks like.

Various classifications about types of uncertainty can be found in the literature. Milliken (1987) defines *state*, *effect*, and *response* uncertainty as uncertainty about the initial or current state, the effect of certain actions, and the resulting response options and utility, respectively. Similarly, Bradley and Drechsler (2014) also focus on three types: *ethical* *uncertainty* where the desirability of decision relevant prospects is unknown, *option uncertainty* describing the uncertainty about relationships between actions, world, and consequences, and *state-space uncertainty* in which the set of all possible states is unknown. Recently, Pelz et al. (2021) conclude that three different types of uncertainty are prevalent in technical systems: *data*, *model*, and *structural* uncertainty. While uncertainty of data refers to model parameters, the difference between model and structural uncertainty can be explained by uncertainty about the functionality of aspects included in the model (model uncertainty) and uncertainty about which aspects should be considered in the model in the first place (structural uncertainty).

All of the mentioned classifications of uncertainty stem from examples which differ slightly from the field of energy system modeling, yet the general structure is also applicable in this field. Therefore, for the purpose of this dissertation three categories of uncertainty will be considered which are derived from the previously mentioned examples, especially from Pelz et al. (2021):

- **Data uncertainty** regards all uncertainty of model parameter values. This includes the current state of the energy system and its components as well as future developments. Data uncertainty originates from either a lack of availability and, subsequently, inherent uncertainty with respect to previous or current data, or from the inherent uncertainty of future developments.
- **Interaction uncertainty** entails everything with respect to model formulation. With energy system models and their equations representing the interactions between different components of the energy system, assumptions are regularly made with respect to the components' behaviour. Often, these assumptions are caused by necessary simplifications in order to keep the model computationally solvable.
- **System uncertainty** describes the uncertainty with respect to the availability and general existence of components and functionalities. Not all future technological, economical, societal, and political tools and developments are already known today but their inclusion in analyses significantly shapes the results. Therefore, they need to be treated with caution as entire outcomes are based on the fact whether a specific option is available or not.

Most energy system models are deterministic, meaning no type of uncertainty is considered in the general model formulation (Prina et al. 2020). What the authors refer to in this statement is the explicit incorporation of uncertainty in the model (*stochastic programming*) which is one way of dealing with uncertainty, especially in data. However, other forms accounting for the previously defined types of uncertainty exist which focus less on the model formulation itself but rather on the analysis performed with the energy system model. What all of these methodologies have in common is that they do not eliminate the uncertainty. They rather provide a way of formulating robust results and findings, taking into account different forms of uncertainty. The following sections will present an overview of these approaches, their strengths and weaknesses, as well as detailing for which type of uncertainty they are best suited for.

1.3.2.1 Scenario analysis

While many definitions of scenarios can be found across the literature, this dissertation will focus mostly on the definition by the United Nations Environment Programme (UNEP): "Scenarios are descriptions of journeys to possible futures. They reflect different assumptions about how current trends will unfold, how critical uncertainties will play out and what new factors will come into play" (UNEP 2002). This definition focuses on two different aspects of scenarios. First, a journey to a possible but not certain future implies that scenario analysis does not only focus on the final state of the system of interest but also on the path towards it. Second, scenarios do not focus on single aspects or components of the system but rather on a set of many different aspects with interactions between them. In the latter case, consistency across all developments is imperative in order for the scenario to be coherent and as realistic as possible.

Scenario analysis is the primary approach found in energy system model analyses across the literature. Examples are the numerous scenarios synthesized in the reports by the IPCC (2022, 2018), the yearly published scenarios in the World Energy Outlook (WEO) by the IEA (2020b, 2021), but also scenario analyses from academia and other research institutes applying scenario analysis can be found (Auer et al. 2020; Ramachandran et al. 2022).

In other cases, scenarios are defined normative, meaning that characteristics of the certain stage or stages of the energy system are predefined and the pathway towards this state is determined by model calculations. This could also be described as implicit scenario analysis, where the outcome does not focus on the final stage (which is, to a degree, predefined) but rather on developments necessary on the path towards this state. Typical examples of GENeSYS-MOD applications using this approach are studies where political or technological climate targets are formulated with different variations thereof. Among others, this can refer to compatibility with different levels of global warming (Hainsch et al. 2021), shares of renewable energies (Sarmiento et al. 2019), or percentages of import dependency (Burandt 2021).

As a result, scenario analysis is a suitable tool to deal with *system uncertainty* but also with the other two forms of uncertainty to a degree. Research questions regarding scenario analysis often ask: "If x and y happen, what are the effects?" or vice-versa: "What would have to happen, if z is to be achieved?" Therefore, effects of the presence of certain developments and components can best be analyzed by this approach which will also be highlighted in Chapters 2 and 3 of this dissertation.

1.3.2.2 Myopic foresight

The concept of myopic foresight explicitly refers to analyses which focus on pathways or any other form of analysis with a temporal dimension in it. It describes an approach where decisions at a given point in time are made without having or accounting for information about the future. It stands in direct contrast to the concept of perfect foresight, in which all future developments and effects of an action can be taken into account. As a result, the solution can be considered a global optimum in the case of perfect foresight, as it represents the optimal allocation of resources over the entirety of the model (Babrowski et al. 2014).

While many energy system models work under perfect foresight (Babrowski et al. 2014), applications of myopic foresight saw an increase in numbers over the past decades (Gerbaulet et al. 2019; Keppo and Strubegger 2010; Babrowski et al. 2014). It can help simulate short-sighted decision making which could be caused by a high focus on short-term developments by policy and decision makers at the expense of long-term benefits (e.g., business plans, election periods). The perfect foresight approach, on the other hand, excels at determining an optimal long-term decision policy, subject to the constraints and assumptions. In contrast to myopic foresight, system inefficiencies caused by short-sighted decisions are eliminated. However, situation with shock-like events or developments are fully anticipated with perfect foresight and could lead to decisions which differ from what can be observed in reality (Thomsen et al. 2021).

Another application of myopic foresight is the reduction of the time horizon of a model to limit the computational complexity. While myopic foresight can be a suitable tool to do '*what-if*' analyses, results analysis should consider the effect of such a massive constraint by, for example, comparing the results with runs under perfect foresight. With energy system models always facing the trade-off between increased complexity and reduced computation time, reducing the model horizon can be one way of keeping complexity in check as is, for example, the case with the LUT model by Bogdanov, Gulagi, et al. (2021). This, however, is not motivated by the desire to account for uncertainty and should, thus, not be considered as such.

In the context of uncertainty, energy system modeling with myopic foresight can be considered as a special case of scenario analysis. The question of "What would happen, if long-term effects and developments in the energy system are not accounted for?" sheds light on *system uncertainty*. Furthermore, the approach can also serve to highlight different aspects of *interaction uncertainty*, since it renders equations regarding future time-periods pointless. Both aspects are highlighted in the subsequent parts of this dissertation (Chapters 4 and 5).

1.3.2.3 Model comparison

With numerous energy system models being used and developed, it becomes important to gain an understanding of their functionalities, strengths, and weaknesses. To allow policy and decision makers to base their actions on robust results, energy system models need to be compared and classified. Various initiatives and communities across the world exist which aim at collecting as many insights from different energy system models, like the Energy Modeling Forum (EMF) or the Energy Climate + Energy Modeling Platform (ECEMP). In general, model comparison can be applied on two levels: on the one hand, their structural features and characteristics and, on the other hand, their results (Prina et al. 2022).

A key difficulty of model comparison is that extensive knowledge about the energy system models is required in order to understand and, subsequently, compare different frameworks. This can either be achieved by the presence of experts (e.g., the developers of a framework or advanced users) or by studying the documentation of each framework. The latter case highlights the necessity for openness, as black-box models can not be evaluated in terms of their structure, making it impossible to assess their functionality and quality. Another challenge might be the different scopes of energy system models which either would have to be considered in the result analysis or avoided by finding a common denominator which is possible to be represented by all frameworks of interest.

Model comparison directly assesses *interaction uncertainty*, since the effects of different model formulations are compared against each other. Studies carried out with a single model using one of the other approaches run the risk of not accounting for model biases. Comparing the results of different models, ideally using an identical set of input parameters and assumptions, can help with identifying these biases and eliminating uncertainty caused by the model formulation which is further exemplified in Chapter 5.

1.3.2.4 Sensitivity analysis

"Sensitivity analysis (SA) is the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input" (Saltelli 2002). In other words, it analyses the relative importance and effect of input parameters on the results (Lam et al. 2020). With many assumptions being made typically on input parameters of energy system models, analyzing their implications through sensitivity analysis is a suitable tool to evaluate the robustness of the generated results.

Quality of data is a major driver of energy system models but comes with a lot of uncertainty, especially regarding future developments of, e.g., costs, efficiencies, and demands. Sticking to the cost example, the price index of lithium-ion batteries decreased by a factor of more than six between 2010 and 2018 (BloombergNEF 2019) with projections consistently underestimating the actual developments (Mauler et al. 2021). Such significant developments are not uncommon in the field of the energy system modeling (e.g., similar developments with PV) extending the need for careful consideration of data assumptions.

Applications of sensitivity analyses are widely spread across the literature (Sanajaoba Singh and Fernandez 2018; Petkov and Gabrielli 2019; Hwang et al. 2021). While mostly consisting of local sensitivity analysis, meaning that single input parameters are changed, calls for global sensitivity analysis are voiced (Saltelli et al. 2019). Both are valuable tools, if used correctly, to deal with *data uncertainty* by spanning a result corridor illustrating the intervals of key results. These intervals can then be used to assess the effectiveness of policy measures targeting the respective parameter which is further elaborated on and exemplified in Chapters 6 and 7 of this dissertation.

1.3.2.5 Stochastic programming

Stochastic programs are programs where some problem data may be considered uncertain (Birge and Louveaux 2011). In this case, data uncertainty refers to data which can be represented as random variables. The uncertainty of the random variable can range from few different scenarios to detailed probability functions. This implicit consideration of uncertainty allows for an integrated analysis since many possible outcomes and combinations of the future system are calculated.

Stochastic problems are typically solved by multi-staged recourse programs, where in each stage decisions are made after the uncertainty is disclosed (Birge and Louveaux 2011). A typical configuration of multi-stage stochastic programming in energy system models is the decoupling of capacity expansion from dispatch and accounting for uncertainty in both stages. Examples in the literature of energy system models are Zhou et al. (2013), Mavromatidis, Orehounig, and Carmeliet (2018), and Skar et al. (2016). Moreover, Burandt (2021) created a stochastic version of GENeSYS-MOD in which effects of hydrogen import availability and prices are analyzed in the case of Japan. Stochastic programming excels at dealing with *data uncertainty* and, depending on the definition of uncertainty of the random variables, also with *system uncertainty.* It is important to note that stochastic programming does not quantify the uncertainty but rather hedges against it. If the reader is further interested in the topic and an application of GENeSYS-MOD using stochastic methods, Burandt (2021) can be referred to.

1.4 The Global Energy System Model (GENeSYS-MOD)

The energy system used for the analyses in this dissertation is the Global Energy System (GENeSYS-MOD). According to the classifications of energy system models by Prina et al. (2020), it belongs in the category of bottom-up models with rich technological detail and sectoral coverage. It is a cost-minimizing, multi-sectoral linear energy system model which minimizes the net present value of the energy system considering various techno-economic and political constraints. Being fully open-source, the framework contributes to open-science and is used by researchers from various organizations[2] for long-term energy system analysis.

GENeSYS-MOD is based on OSeMOSYS by Howells et al. (2011a), which in turn is similar to the widely known MARKAL-TIMES family of models (Loulou, Goldstein, and Noble 2004; Loulou et al. 2005). In its first application in 2017, GENeSYS-MOD was applied to analyze the possibility of a global energy system based on 100% renewables in 2050 (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017). However, despite the name suggesting otherwise, GENeSYS-MOD is not limited to global analyses. With the generic nature of the frameworks equations, data is the determining factor differentiating different regional case-studies. As a result, many applications of GENeSYS-MOD over the past years analyze different regional energy system transformations, including globally (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017), Europe (Hainsch et al. 2021), Germany (Bartholdsen et al. 2019), Norway (Sørbye and Weisz 2021), South-Africa (Hanto et al. 2021b), India (currently in revision), China (Burandt et al. 2019), Japan (Burandt 2021) and Mexico (Sarmiento et al. 2019). In some of these case-studies, entire countries or even continents are aggregated into single nodes, while higher spatial disaggregation is applied in country analyses where states or regions are used as nodes, depending on shared characteristics. Therefore, data availability and research question determine the scope of an application of GENeSYS-MOD which could also be applied for small urban areas or villages.

One determining characteristic of GENeSYS-MOD is its multi-sectoral approach, covering the electricity, buildings, industry, and transportation sector. While the traditional energy system did not consist of many interconnections between the sectors, the emergence of

[2]To my knowledge, these organizations consist of: TU Berlin, DIW Berlin, Europa Universität Flensburg, NTNU Trondheim, Statkraft, as well as being considered in SINTEF and EDF

sector-coupling requires an integrated approach to account for interactions between all energy sectors. A plethora of technologies for all sectors is included in the model, while sector coupling technologies serve as connectors between them. Figure 1.3 showcases a basic overview of the model structure.

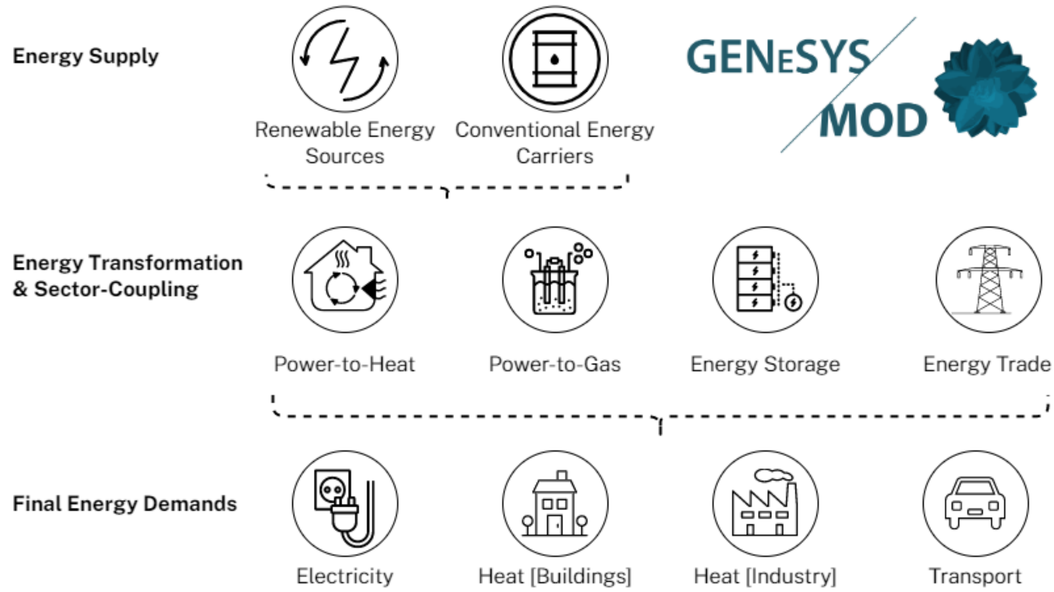

Figure 1.3: Model structure of GENeSYS-MOD. Source: Own illustration.

GENeSYS-MOD operates on two different levels with respect to the optimization of future energy systems. On the one hand, capacity planning is carried out, determining the optimal capacity investments over the entire modeling period and for all sectors. On the other hand, energy generation (dispatch) is optimized for each timestep, ensuring that energy demand is covered at all times. Both are optimized simultaneously and, thus, affect each other which increases the computational complexity significantly but guarantees an overall optimized system. The objective function (see Equation 1.1), therefore, minimizes the total discounted costs associated with capacity expansion, energy generation, storage, transmission, and transformation for all regions (r), technologies (t), and years (y). The total discounted technology costs include capacity expansion cost, variable and fixed O&M costs, fuel costs, a salvage value which determines the remaining value of capacities in the final model period, and costs caused by emissions. For trade costs, capacity expansion, O&M costs, and the salvage value are considered.

$$\min z = \sum_r \sum_t \sum_y TotalDiscountedCost_{r,t,y} + \sum_r \sum_y TotalDiscountedTradeCosts_{r,y} \quad (1.1)$$

Equation 1.1: Objective function of GENeSYS-MOD.

Since its original formulation which was closely following the OSeMOSYS structure, many features were implemented to GENeSYS-MOD to improve its functionality. Figure 1.4 depicts the evolution of the framework together with the corresponding versions. In the early stages of GENeSYS-MOD, development mainly focused on improvements of various functionalities as the baseline OSeMOSYS formulation was found to be too inflexible and inaccurate. A significant change was implemented in Burandt, Löffler, and Hainsch (2018) and thereafter in Burandt et al. (2019) where the original temporal resolution was changed: First, the number of time-slices was increased from 6 to 16, allowing a more accurate representation of inner-daily variability. Second, the entire time-slice approach was replaced by a time-series formulation coupled with a time-series reduction algorithm based on Gerbaulet and Lorenz (2017), allowing a flexible, up to hourly, time-resolution. This allowed for the inclusion of ex-post dispatch calculations and in recent projects GENeSYS-MOD was used in a fully hourly dispatch optimization (see Chapter 5 for further information). Other changes include better sectoral representation like for industry (Bartholdsen et al. 2019; Burandt 2021) or transportation (see Chapter 7) as well as a constant process of performance optimization to allow for more complex analyses. The block structure of GENeSYS-MOD is represented through modules in the source code, which in many cases allows flexible and use-case specific configuration of the model, since these modules can be turned on or off depending on data availability and desired complexity. These modules either improve on existing formulations (e.g., the public transport upgrade) or add new functionalities (e.g., the reduced foresight module). In either case, the model is able to run with or without them being switched on since they are not essential to the general model formulation.

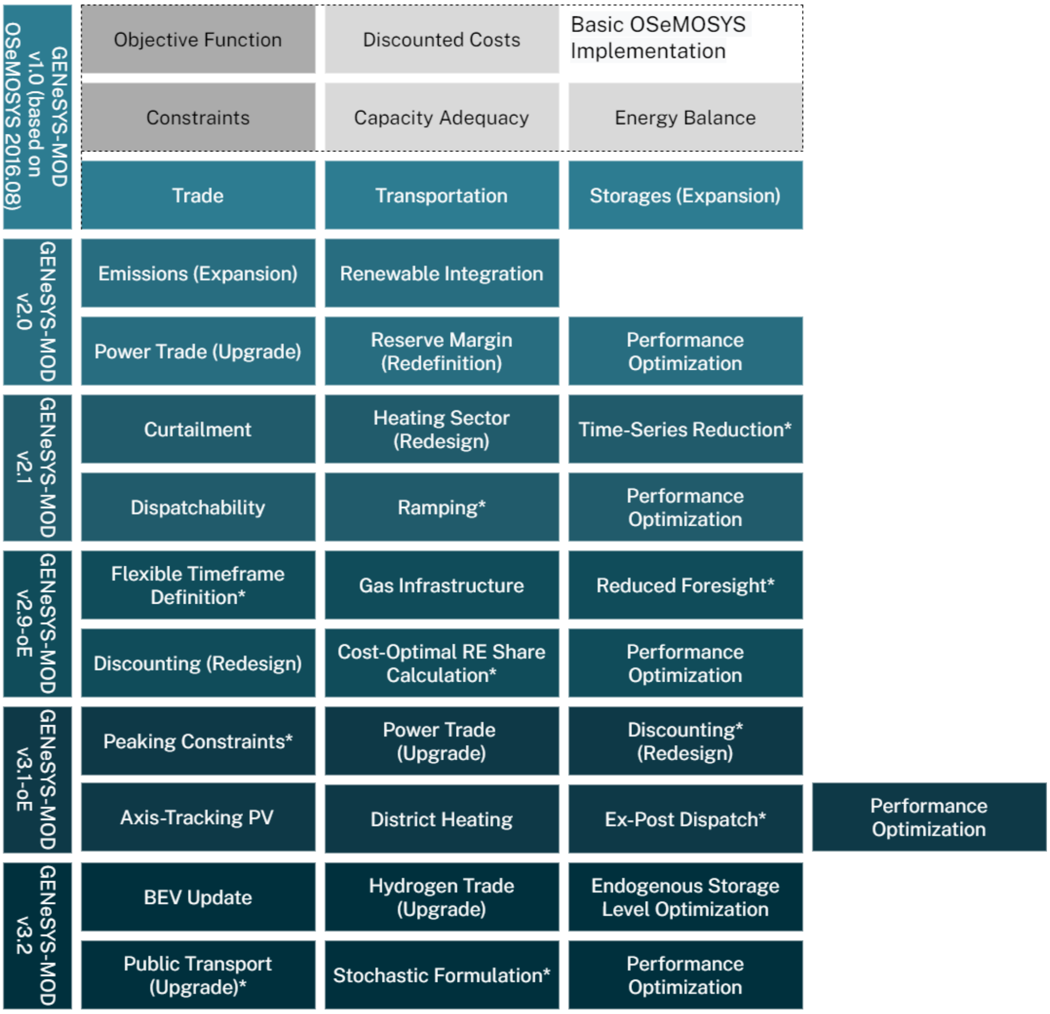

Figure 1.4: Block structure and additions of GENeSYS-MOD. Blocks marked with an asterisk are separate modules which can be switched on and off. Source: Own illustration.

As described in the previous section, the category of deterministic energy system models, to which GENeSYS-MOD also belongs, faces the issue of a lack of uncertainty consideration in the basic model setup. Therefore, different approaches were applied in analyses with GENeSYS-MOD. Scenario analysis dominates the studies with some examples being Auer et al. (2020), Hainsch et al. (2021), and Bartholdsen et al. (2019). In some cases, the scenarios are less elaborated and rather reflect different climate targets which, in turn, leads to different results in the energy system configuration. Sensitivity analyses were carried out in two case-studies focusing on Germany with the findings being described in this dissertation's Chapters 6 and 7. Löffler et al. (2019) showcase the effects of myopic foresight using the GENeSYS-MOD framework which can be found in Chapter 4. Lastly, direct accounting for uncertainty was performed by Burandt (2021), analyzing the potential and necessity for hydrogen imports in Japan through means of stochastic programming.

In summary, all of the mentioned papers and studies verify the possibilities GENeSYS-MOD offers in terms of accounting for uncertainty in future energy systems, which makes it an ideal tool for the analyses carried out in this dissertation. Furthermore, it is openly available and documented[3] with regional data-sets being published alongside the corresponding studies. Contributing to open-science by allowing other researchers to verify, validate, and reproduce results, it is a powerful tool which will continue to be developed in order to assist with the low-carbon transformation of the energy system.

1.5 Outline of this dissertation

This dissertation provides an in-depth overview of the German and European low-carbon transition. Therefore, the following chapters are separated into two parts. Part I, consisting of Chapters 2-4, takes a look at 100% renewable pathways with a focus on Europe and aims to synthesize common findings across different applications. Thereafter, Part II contains Chapters 5-7 and dives into the German energy transition, highlighting chances and barriers for it's success. Across all of these studies, different methodologies to account for different types of uncertainty are applied, leading to robust findings which are detailed further in Section 1.6. Figure 1.5 visualizes the structure of this dissertation.

[3] For further information and documentation, model code, and sample data set, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public

Figure 1.5: Outline of the dissertation. The Chapters in Part I and II are based on peer-reviewed academic publications. Chapter origins as well as own contribution are detailed in Section 1.5.3

1.5.1 Part I - European energy system scenarios for 100% renewable energies

The first part of this dissertation encompasses three papers which focus on European energy scenarios and analyses of 100% renewable energy systems. Chapter 2 summarizes findings and lessons learned from modeling energy systems based on 100% renewables and draws methodological conclusions which were applied for all following chapters. Next, Chapter 3 showcases results for European decarbonization pathways, outlining common findings across multiple studies and recommendations for further policy action. Lastly, Chapter 4 analyzes the implications of short-sighted policy and decision making, highlighting the need for long-term consideration of decisions regarding the energy system.

1.5.1.1 Chapter 2: Lessons from modeling 100% renewable scenarios using GENeSYS-MOD

In this chapter, characteristics and challenges for energy system modeling of 100% renewable scenarios are showcased, serving as a basis for all further analyses in this dissertation. The concept of energy systems based on 100% renewable energies experienced a substantial increase of interest in the last decades. While initially questioning the feasibility of such systems, researchers now focus on specific assumptions and configurations of 100% renewable energies. With the main aim of models being to provide insights, not numbers, complexity only increases through the potential and need for sector coupling, international connections, and a rapidly changing energy system. However, most calculations are bound by the computational resources available to the researchers, leading to a trade-off between all possible sources of complexity. Therefore, this chapter highlights results from analyses with GENeSYS-MOD, aiming to better understand and interpret existing models as well as to improve future modeling exercises.

First, the spatial resolution plays a significant role in the configuration of the future energy system, especially with respect to the distribution of different renewable technologies. Aggregations on heterogeneous regions in terms of renewable energy potential, like continental Europe for example, can lead to less differentiated results since information about regional particularities are lost. An often observed result of energy system models with 100% renewable energies is the reliance on higher shares of wind on- and offshore in northern regions, while southern regions are usually dominated by higher shares of PV. Interestingly, this holds true for analyses on a global, continental (i.e., Europe), and German level. Considering these regional particularities becomes even more important, since the added dimension of social acceptance (e.g., power transmission lines, local loss of jobs in the energy industry) becomes more pronounced the higher the spatial resolution.

Second, similar to spatial resolution the choice of temporal resolution is equally as important. Lower temporal resolution, caused by one of many forms of time-series reduction algorithms, could lead to the loss of regional particularities like, for example, the monsoon season in India. Another aspect regarding temporal resolution is the often made assumption of perfect foresight of energy system models. Long-term implications and effects of investment decisions are assumed to be ”known”, which does not necessarily reflect the actual behaviour of interested parties, as will also be described in more detail in Chapter 4. Furthermore, sectoral analyses as well as the consideration of socio-political factors can help significantly in gaining a better understanding of particularities of energy systems based on 100% renewable energies.

1.5.1.2 Chapter 3: Review and comparison of European energy transition scenarios

This chapter analyzes and compares results of different European energy transition pathways and analyzes the ambitions of the EGD in the three areas of society, policy, and technology. With a rising number of studies focusing on a highly or fully decarbonized European energy system, the landscape of results and recommendations becomes increasingly diverse. Assumptions about decarbonization targets, socio-political, and techno-economic context greatly influence pathway perspectives and their main narratives. However, these assumptions are not always communicated in a clear and comprehensive way, leading to misinterpretation of results and conclusions.

In this work, a wide range of European energy transition studies is analyzed with respect to underlying assumptions on GHG emission reduction targets and technological, policy, and societal assumptions. The latter three dimensions are then used to define a novel, three-dimensional scenario generation approach which is applied to generate four European energy transition pathways as part of the openENTRANCE project. Auer et al. (2020) highlight the main results of this pathway quantification. Among other findings, the results suggest that rapid transformation of the energy system is required and that climate action in the near future can reduce the overall required effort in the later periods. Moreover, despite differences regarding input assumptions and decarbonization targets, all pathways show similar results in multiple categories, like primary energy demand, electricity generation, or required storage capacities.

Comparing the results of the four scenarios with three other European scenarios achieving 100% GHG reduction by 2050, the effects of input assumptions on the model results become more apparent. However, similar results in terms of final energy consumption, electrification rate, and power capacities suggest that electrification of all energy sectors coupled with an expansion of renewable energies will be the backbone of a decarbonized European energy system. Mirroring these results against the ambitions of the EGD, this chapter finishes by highlighting areas which require more emphasis if said decarbonization is to be achieved.

1.5.1.3 Chapter: 4: Assessment of the stranded assets problem in Europe through myopic foresight

Following the analysis of different European energy transition pathways and a synthesis of which areas policy makers should put additional emphasis on, this chapter addresses the effects of short-sighted decisions on the energy system. Many studies, also in this dissertation, show that rapid and immediate action is required to keep global warming as low as possible. Increasingly more ambitious climate targets coupled with the technological development of renewable energy sources (RES) can lead to existing fossil capacities being shut down before reaching their economic lifetime, thus, becoming stranded assets. This chapter contributes to this issue by analyzing to what extend short-sighted decision making leads to investments into fossil capacities which will end up being stranded assets in the future as they need to be decommissioned to comply with climate targets.

Therefore, GENeSYS-MOD is expanded by a module enabling myopic foresight in the model. The first two investment decision periods do not take long-term effects of capacity expansion into account, with the optimization being limited to the considered period. After the year 2030, however, the overall GHG budget is introduced and has to be complied with. Three different scenarios are introduced, representing a baseline (*BASE*) scenario following political targets under the assumption of perfect foresight, a reduced foresight (*RED*) scenario which introduced the above described approach, and a scenario with further delayed political action under reduced foresight (*POL*) representing the influence various incumbent actors might have on decision making.

The comparison of the three scenarios results suggest that reduced foresight does affect the short-term decision making process. In the scenarios *RED* and *POL*, significant amounts of stranded coal- and gas-fueled power plants can be observed across Europe. For both lignite and coal-fired power plants, between 58 GW and 66 GW of unused capacities remain in 2030. Moreover, the load factor of fossil capacities decreases after 2025 with short-sighted decision making, making those capacities which are not stranded less efficient, nonetheless. Caused by the increased usage of fossil fuels until 2030, emissions need to be reduced faster thereafter in the *RED* and *POL* scenario, putting additional stress on the energy system which could have been avoided by long-term considerations. This further increases the need for strong and clear signals from policy makers to prevent construction of unnecessary fossil-fueled power plants.

1.5.2 Part II - Germany's energy system transformation: chances and barriers, challenges, and policies

Following the European analyses, this part focuses on the characteristics of the German low-carbon energy system transformation and key challenges of the transition. Chapter 5 compares five open-source energy system models and draws conclusions about the bias of results caused by model formulation and design. Thereafter, Chapter 6 provides a detailed analysis of potential chances and barriers of the German system transformation by analyzing the effects of various input parameters on model results. Lastly, Chapter 7 extends this approach by providing an in-depth analysis on the German transportation sector and detailing areas to target for policy makers to facilitate the mobility transition.

1.5.2.1 Chapter 5: Model comparison on the German energy system transformation

This chapter addresses the 2030 climate targets set by the in 2021 elected German government by comparing results of five different open-source frameworks. Most scenario analyses consist of a set of differing input assumptions which are processed by the same framework to generate insights on the effects of said assumptions. However, framework formulation and particularities might have a significant effect on the results. This bias can hardly be accounted for when comparing results from a singular framework, as it might be unclear whether determined no-regret options are caused by framework particularities or the actual dynamics of the energy system. To address this bias, this chapter compares results of five energy system models all using the same input data and assumptions to analyze Germany's 2030 climate targets.

Since the five considered frameworks (*GENeSYS-MOD*, *Balmorel*, *Genesys-2*, *oemof*, and *urbs*) are used for different use-cases and research questions, the analysis focuses on a set of data and assumptions which can be implemented by all frameworks to ensure comparability. This process of data and model harmonization highlighted the complexity of the frameworks, as even in the presence of the framework developers it proved to be difficult to fully understand all the intricacies of the frameworks required for this task. Open and clear communication of framework components and functionalities as well as ensuring usability are found to be key in order to enable wide-spread use of open-source energy system models (Berendes et al. 2022; Candas et al. 2022b).

In this chapter, the German power sector of 2016, 2030, and 2050 is considered with special focus being set on the 2030 climate targets. The results highlight that model formulation and degrees of freedom can have significant effects on specific elements of the energy system.

In particular, the degree to which specific flexibility options such as storage, transmission, or curtailment are used differed between the frameworks. Consequently, the landscape of power generation technologies is affected slightly. With one framework being based on a simulation instead of an optimization (*Genesys-2*), differences in investment behaviour could be observed which mirror those of reduced foresight optimization discussed in section 4. However, the overall results show a lot of similarities across all frameworks, proving their robustness and highlighting important aspects of the 2030 German energy system.

1.5.2.2 Chapter 6: Chances and barriers for Germany's *Energiewende*

Following the analysis of how different framework parameters and design decisions affect results of energy system models, this chapter examines the effects of key data-based parameters to determine key influential factors for the German energy transition. Numerous components of the likely future energy system are still accompanied by a high degree of uncertainty, both in terms of their techno-economic parameters as well as general availability and societal acceptance. Energy system models frequently have to assume cost, efficiency, and availability of these components which have substantial influence on the shape of the results. Therefore, an extensive sensitivity analysis of these parameters is presented in this chapter, highlighting their magnitude and significance on the overall results.

Consequently, eleven core parameters are altered in this analysis, ranging from energy demands over costs and potentials for renewable energies to the development of carbon prices and renovation rates for residential and commercial buildings. Rather than singular results, this approach spans a *result corridor*, showcasing the effect of the underlying assumptions. A base case is computed and serves as comparison as well as the starting point for the sensitivities. Contrary to the previous chapters, this base case does not comply with set climate targets which still results in small amounts of emissions in 2050. This, however, allows for a more comprehensive analysis of the sensitivities, as enough room for changes is available in both directions.

The results suggest that energy demand reductions play a tremendous role in achieving climate targets. Similarly, cost and potentials of renewable energies show significant influence on generation cost, necessity of grid expansion, as well as regional distribution of power generation capacities. The choice of carbon price has higher effects in the short to intermediate term and affects certain sectors (i.e., industry) stronger than others.

1.5.2.3 Chapter 7: Identifying policy areas for the transition of the transportation sector

Similar to the previous chapter, this chapter applies the methodology of exploratory sensitivity analysis to analyze the effects of uncertain parameters on the transportation sector in particular. Being the only sector in Germany where emissions in 2019 were still around 1990 levels, the transportation sector faces the challenging task of massive emission reductions to comply with the 2030 targets set by the government. Road transportation is responsible for most of these emissions, yet decarbonization options are still in the early stages of market penetration (e.g., BEVs) or still in development (e.g., freight transportation). As a result, uncertainty dominates the future transportation sector but action is required today since emissions need to be reduced significantly in less than a decade.

Four key areas of uncertainty are identified affecting the future transportation sector: transportation demand, modal split across the modes of transportation, fossil fuel and carbon prices, as well as hydrogen availability and costs. Sensitivity analysis for these four areas is conducted and six key performance indicators (KPIs) serve to analyze their results. Additionally, the representation of the transportation sector in GENeSYS-MOD is updated to allow for a better representation of the public transport sector and electric vehicles.

Transportation demand, again, proves to have the most significant effect on many aspects of the energy and transportation system, such as energy consumption, emissions, vehicle fleet size, and hydrogen production. A more pronounced modal shift can help reducing emissions in the intermediate term, as rail-based modes of transportation are already electrified to a large degree offering higher decarbonization potential than road-based transportation. This shift also comes with a significant reduction in energy demand, reducing the dependency on energy imports. Similar to the findings of the previous chapter, a carbon price shows highest effects in the intermediate term, facilitating a rapid shift from fossil technologies to renewables. Policy makers should therefore focus on the cost of fossil fuels, advantages of public transport and rail transportation to reduce emissions in the short term, while the long term priority should be reducing the need for transportation in the first place.

1.5.3 Chapter origins and own contributions

Table 1.2 presents the publications of the dissertation's chapters, as well as further information of the own contributions for each chapter. Additional publications which are not part of this dissertation but were co-authored by me in the same time period can be found in Table A.1. Furthermore, source-code and documentation of GENeSYS-MOD can be found at the public GitLab page (https://git.tu-berlin.de/genesysmod/genesys-mod-public).

Table 1.2: Chapter origins

Chapter	Pre-publications & Own Contribution
2	**Lessons from modeling 100% renewable scenarios using GENeSYS-MOD**
	This chapter is based on an article under the same name in *Economics of Energy and Environmental Policy* 9 (1), 2020
	Joint work with Pao-Yu Oei, Thorsten Burandt, Konstantin Löffler, and Claudia Kemfert. The authors contributed equally to this work: conceptualization, methodology, investigation, visualization, writing - original draft preparation. P.-Y. O. , T. B., and K. L. managed the review and editing process.
3	**Review and comparison of European energy transition scenarios**
	This chapter is based on: ”Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal?” *Energy* 239 (Part C): 122067, 2022
	Joint work with Konstantin Löffler, Thorsten Burandt, Hans Auer, Pedro Crespo del Granado, Paolo Pisciella, and Sebastian Zwickl-Bernhard. Conceptualization was carried out by K. H., H. A., and P. CdG. Development of methodology was performed by H. A., P. CdG., and S. Z.-B.; P. P. researched relevant literature. Data Curation was performed by T. B., result validation by K. L., T. B., and P. P. Result visualization was carried out by S. Z.-B; K. H. and K. L. wrote the original draft and K. H. and H. A. managed the reviewing process.
4	**Assessment of the stranded assets problem in Europe through myopic foresight**
	This chapter is based on: ”Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem”, *Energy Strategy Reviews* 26 (November), 2019
	Joint work with Konstantin Löffler, Thorsten Burandt, and Pao-Yu Oei. K. L. initiated the research. Conceptualization was carried out jointly by all authors. K. L., T. B., and K. H. defined the scenarios. Writing of the paper was carried out by K. L., K. H., and T. B.; T. B. provided the literature review, scenario definition, and parts of the result description. K. L., T. B., and K. H. extended the model and carried out the model runs. K. L., T. B., and K. H. performed the data research process. T. B. and K. L. managed the review and editing process.

Table 1.2: Chapter origins (continued)

Chapter	Pre-publications & Own Contribution
5	**Model comparison on the German energy system transformation**
	This chapter is based on: ”Comparing open source power system models - A case study focusing on fundamental modeling parameters for the German energy transition”, *Renewable and Sustainable Energy Reviews* 161 (2022): 112331
	Joint work with Jonas van Ouwerkerk, Soner Candas, Christoph Muschner, Stefanie Buchholz, Stephan Günther, Hendrik Huyskens, Sarah Berendes, Konstantin Löffler, Christian Bußer, Fateme Tardasti, Luja von Köckritz, and Rasmus Bramstoft. Conceptualization was carried out by J. v.O. The methodology was developed by J. v.O., K. H., S. C., S. G., K. L. and S. Be.; J. v.O., K.H., S. C., S. G., K. L., and R. B., were responsible for model runs. Data curation was performed by K. H., C. M., S. Bu., H. H., L. V.K., and F. T. Writing of the manuscript was carried out by J. v.O., K. H., S. C., K. L., S. Be., L. v.K., and R. B. while the review process was managed by J. v.O., K. H., S. C., C. M., S. Bu., H. H., K. L., S. Be., C. B., and R. B.
6	**Chances and barriers for Germany’s *Energiewende***
	This chapter is based on: ”Chances and barriers for Germany’s low carbon transition - Quantifying uncertainties in key influential factors”, *Energy* 239 (Part A): 121901, 2022
	Joint work with Konstantin Löffler, Thorsten Burandt, Pao-Yu Oei, Felix Wejda, and Frederik Seehaus. K. L. conceptualized the paper and initiated the research. Scenario definition was carried out jointly by all authors. K. H., K. L. and T. B. wrote the paper. Pre-submission review and proof-reading was handled by K. H., K. L., T. B., and P.-Y. O. The data research was carried out by F. S., F. W., K. H., K. L., and T. B. K. H., K. L., T. B., and P.-Y. O. managed the submission and review process.
7	**Identifying policy areas for the transition of the transportation sector**
	This chapter is under review in *Energy Policy* using the same title.
	Single author original research article.

1.5.4 Novelty of this work

This dissertation contributes to the existing literature and research by providing robust insights on the European and German energy transition. The robustness is ensured by a variety of methods which account for different types of uncertainty in the present and future energy system. *Data uncertainty* is tackled in Chapters 6 and 7, *interaction uncertainty* in Chapters 2 and 5, and *system uncertainty* analyzed in Chapters 2, 3, and 4. By assessing the effects of all types of uncertainty, conclusions can be drawn which hold true across many calculations, identifying no-regret options and informing policy makers about potential areas to focus on. Furthermore, the principles of open science are followed by making model source code, data, and publications open access, supporting the findings in a transparent way for everyone to validate. In doing so, I hope to contribute to the scientific, public, and political debate about the European and German energy transition.

1.6 Key findings and conclusions

1.6.1 What are best-practices regarding energy system modeling with 100% renewables and what can be learned from them?

Three main outcomes can be identified regarding the question of what energy system modelers should consider when providing analysis of energy systems based on 100% renewables. The principles of open science should be followed to allow for accurate assessment of the results. This especially becomes important when accounting for uncertainty, which should always be done to add robustness to the results. Lastly, the level of disaggregation in a model highly influences the results and should always be tailored towards the goal of the analysis.

1.6.1.1 Open science is highly beneficial in energy system modeling, yet not applied enough

With energy system models and their results supporting today's climate and energy policies, it is imperative that assumptions, biases, and results are communicated as clearly as possible. Open science, consisting of the three pillars open data, open source, and open access, allows for validation and verification of methodologies and results by others. Even for experts in the field, it becomes increasingly difficult to fully understand the complexity of and interaction within other models. Consequently, the analysis in Chapter 3 was only possible after private consultation of the authors of the studies used for the comparison. As a result, policy and decision makers face an even greater challenge if they want to extract all the relevant information from studies if they are not well documented and summarized. Therefore, researchers and practitioners need to take responsibility for adequate assumption and result communication of their energy system analyses.

1.6.1.2 Accounting for uncertainty adds layers of robustness to results such that policy makers can base their decisions on these results

In a field dominated by numbers and deterministic models, it is important to put results into perspective and focus on the insights gained by said models. Uncertainty can not only be present in assumptions with respect to data but also in system interactions which are always, to a degree, simplified in all types of models. Out of the different methodologies to account for uncertainty presented throughout this dissertation, none is strictly better than the other. They rather complement each other adding robustness to the results as well as the overall methodology. The benefit of accounting for uncertainty in model formulation and assumptions is therefore twofold: On the one hand, modelers gain a deeper understanding of the functionalities of their model as well as the interactions of the different parts of the energy system. On the other hand, policy and decision makers can base their actions on more robust analyses and findings instead of singular calculations. Using, for example, myopic foresight (see Chapter 4) and compare the results to runs under perfect foresight can provide insights into the effects of short-sighted decision making.

1.6.1.3 Level of disaggregation highly impacts results and should always be considered

The choice of disaggregation level can significantly shape the outcome of model results and needs to be considered when drawing conclusions from analyses with energy system models. Temporal, spatial, and sectoral resolution all affect the calculation and results of lower levels of disaggregation are not necessarily applicable for higher levels. As an example, the findings in Chapter 2 highlight that results of a global analysis suggest equal shares if wind onshore, wind offshore, and PV for Europe, while detailed calculations for Europe showcase a regional differentiation with PV dominating the southern regions and wind the northern ones. Going one step further, the effect can be observed when comparing results on the European level with those of Germany. With the availability of computational resources typically being the limiting factor in terms of levels of disaggregation, the different levels need to be considered carefully. The resulting configuration has to be adequate to answer the initial research question while allowing for the highest degree of detail computable.

1.6.2 What challenges arise for the German energy system transformation and which areas are of specific interest for policy makers?

The success of Germany's energy transition depends on many factors, with three key takeaways from the subsequent chapters being highlighted here: First, Germany might miss the 1.5°C climate target in the next 3-8 years, depending on the methodology to determine the budget. Second, energy demand reductions show high potential for the overall success. Third, the role of hydrogen depends highly on the development of production and import costs.

1.6.2.1 Germany is at risk to miss the 1.5°C emission target as early as 2025

Climate targets are, next to decarbonization levels, a primary focus in the public debate about climate policy. The analyses in Chapters 3, 6 and 7 all show that an emission budget corresponding to global warming of 1.5°C is substantially more difficult to achieve, than of 2°C. Depending on the methodology chosen for determining national GHG budgets, Germany could reach said budget by 2025. Even a budget compatible with global warming of 2°C requires a complete transformation of the energy system until midst of this century. That being said, failing to reach a 1.5°C climate target should not discourage from aiming for as few emissions as possible. Since the effects of global warming can already be observed today, limiting these effects as much as possible should be the primary goal of today's energy and climate policy.

1.6.2.2 Energy demand reductions show high potential for the decarbonization's success, carbon prices mostly in the intermediate years

Energy system models typically focus on techno-economic parameters of the energy system, yet energy demand and sufficiency aspects could prove to have the highest impact for a successful decarbonization of the energy system. A reduction of energy demand avoids the need for the energy generation technologies which would be required in the first place. Or to say it in other words: the best kilowatt hour is the one we don't need. In the periods from the early 2020s until 2050, demand reductions can directly avoid the use of fossil fuels which are still present in all sectors of the energy system, while in later periods the stress put on sectors which are difficult to decarbonize can be reduced. Furthermore, a carbon price can help in the early years to facilitate a shift from fossil to clean technologies. By shifting the relative costs in favour of renewable energies, important investments into clean technologies could be facilitated instead of fossil infrastructure which would become stranded shortly thereafter.

1.6.2.3 Hydrogen import costs of below 2€ per kilogram could lead to widespread application of hydrogen

Hydrogen is often considered a cornerstone of an energy system based on 100% renewable energies, serving as a flexibility option in the power sector as well as fuel for areas where direct electrification is not feasible. However, hydrogen generation and possible re-conversion comes with significant energy losses due to conversion inefficiencies which in turn increases the amount of required power capacities to produce the hydrogen. Therefore, the role of hydrogen could be limited to the sectors where alternatives are scarce (e.g., industry or freight transportation) without meaningful impact outside of that. In the case of cheap hydrogen imports (i.e., around or less than 2€ per kilogram), its application could spread to other areas in the energy system, although raising questions about the effects of these imports in the countries of origin. Overall, the future importance of hydrogen is characterized by a lot of uncertainty and needs further careful analysis.

1.6.3 Which no-regret options can be observed across multiple different analyses regardless of input assumptions or scenario definitions

Since all of the chapters pathways for the energy system transformation, common findings can be synthesized from the analyses. Renewable energies need to be expanded rapidly, with fossil fuel capacities having to be phased out at the same time. Delaying this phase out results in significant increase in costs due to the possibility of stranded assets. Therefore, electrification will play a major role across all energy sectors (e.g., motorized private transport) with hydrogen and synthetic fuels complementing in areas which are difficult to electrify.

1.6.3.1 No new fossil fuel capacities are required, rather a rapid expansion of renewables coupled with flexibility options

To achieve the rapid decarbonization described in the previous paragraph, it is important to avoid any new investments into fossil infrastructure and technologies and rather facilitate their quick phase-out in favour of renewable energies. Additional investments into fossil capacities will lead to significant amounts of stranded assets in the near future, coupled with a reduced load factor and, thus, profitability of existing fossil capacities. Naturally, some sectors are easier to decarbonize than others, since the primary options are already available today. Therefore, in the upcoming years, the focus should primarily lie on decarbonizing the electricity sector by a fast expansion of renewable energies, reducing building energy demand through insulation improvements, and promoting a shift from motorized private transport to public transport and rail-based options in general. The electricity sector needs to be decarbonized between 2030 and 2035 to achieve climate targets. Flexibility options in terms of storage or grid expansion support this transition.

1.6.3.2 There is no room for delayed action, delaying action by 5-10 years results in a cost increase of as many percent

Across all papers presented in this dissertation, the need for an immediate and rapid decarbonization of the energy system is showcased. Especially Chapter 4 highlights the effects of delayed action, leading to additional efforts necessary in later periods if climate targets are to be achieved. This leads to increased costs, higher stress on the energy system transformation in the later periods, as well as the potential of triggering tipping points which would be near impossible to revert. With ambitious targets set by the EU and Germany for 2030, this necessity is, at least in part, acknowledged by policy makers. However, discussions about the compatibility of said political climate targets with limiting global warming to below 1.5°C or 2°C as well as about the chance of success to reach them until 2030 highlight the need for additional efforts. Energy system modelers can help supporting these efforts by informing policy and decision makers through robust, transparent, and differentiated results.

1.6.3.3 Electrification is key in all sectors, coupled with renewable electricity generation

Technologies using fossil fuels need to be replaced by other options that do not emit GHG. Next to synthetic fuels and hydrogen, which, as discussed, could play an important role but are tied to a lot of uncertainty, direct electrification promises to be the most efficient and effective way of decarbonizing the energy system. Since electricity-consuming technologies are only as clean as the electricity that fuels them, the power sector needs to be decarbonized to a high degree to effectively reduce emissions. Typical application of direct electrification across all sectors include heat pumps for buildings, electric vehicles and trains for transportation, as well as electric arc furnaces or similar options for industry. Moreover, electricity-fueled technologies usually possess higher energy conversion efficiencies than their fossil counterparts, reducing the amount of primary energy required and possibly also reducing import dependencies. This transformation needs to happen simultaneously across all sectors, starting with the technologies already available today. Synthetic fuels and hydrogen support where electricity is not suitable like parts of transportation or in industry.

1.6.3.4 BEVs will likely be the dominant motorized private transport technology

Currently dominated by combustion engine relying on oil derivatives, the future of motorized private transport will be electric. While some argue for synthetic fuels as a replacement for gasoline and diesel or fuel-cell electric vehicles (FCEVs), battery elctric vehicles (BEVs) are too beneficial and will most likely be the only technology deployed on a large scale. On the one hand, BEVs have high synergy with renewable energies through the possibility of smart charging. BEVs could become of even further use as two-way flexibility option if bi-directional charging is enabled in the future. On the other hand, energy losses in the conversion process of hydrogen or other synthetic fuels deems them less energy efficient and, thus, more expensive. Currently perceived disadvantages of BEVs compared to their alternatives might become obsolete (e.g., charging infrastructure which will improve with higher shares of BEVs) or improved on (e.g., driving range and battery lifetime). Without significant cost reductions compared to typical assumptions (i.e., below 2€ per kilogram), hydrogen will remain important in other transportation sectors without being relevant for motorized private transport.

1.7 Shortcomings and research outlook

1.7.1 Shortcomings of the presented work

Various shortcomings of the presented dissertation need to be pointed out to paint a clearer picture of the strength and especially weaknesses of the analyses provided. First, the limitations of the chosen level of disaggregation in terms of temporal, spatial, and sectoral are not suited to provide consistent results on a local level. As described in Section 1.3.1, the various levels of disaggregation typically compete for a limited amount of computational resources, causing a trade-off between them. In almost all applications of GENeSYS-MOD throughout this dissertation, sectoral degree of detail is quite high with electricity, buildings, industry (up to three different categories), and transportation (freight and passenger as distinct categories) all being considered. With respect to spatial disaggregation, between 10 and 30 nodes are considered in all analyses. As a result, temporal degree of detail (i.e., the amount of time steps within a year) is the residual form of disaggregation and is adjusted in such way that the model is kept computable while offering the best temporal resolution. An exception of that is the analysis in Chapter 5, where a fully hourly resolution was made possible by calculating single years and disregarding a pathway development. And while analyses on different levels of disaggregation help with determining robust results (see Chapter 2), one needs to keep the simplifications made in mind when interpreting the results.

The other end of the spectrum when it comes to aggregation is also neglected to some degree. Global warming and the climate crisis are, as the name suggest, a global crisis and, in turn, require global answers. In the current world where economies and societies are more and more interconnected, no country or region is isolated from the rest of the world. The current situation in a world stuck by a global pandemic and a war in Ukraine brutally showcases that events in other parts of the world can have significant effects on countries, regions, continents, or the entire globe. These, but also less extreme, interactions are typically ignored to a certain extend in the presented Chapters, since they occur at the boundaries of the model analyses and are, therefore, characterized by assumptions.

Another aspect which is similar to the one of disaggregation levels is the chosen model class and the shortcomings it comes with. GENeSYS-MOD is a linear optimization problem which takes the perspective of a central planner who is only concerned about the overall optimal configuration of the system. On the one hand, linear program's key characteristic in terms of modeling is that they are by far the easiest to compute but limit the possibility of representing real-life processes and properties. By linearizing all interactions within the energy system, non-linear, integer, or binary properties can not be considered or are simplified significantly, as is for example the case for infrastructure enabling certain activities like additional rail tracks, charging infrastructure, or overhead power lines. On the other hand, the central planner perspective disregards different, sometimes competing, interests and objectives of the various actors in the energy system. The optimal result of linear programs always lies in an extreme point of the possible solution space (i.e., at least one corner) while in reality compromises are formed to accommodate various parties and stakeholders. Other forms of modeling approaches are better suited to depict these interactions like, for example, complementarity models.

Lastly, GENeSYS-MOD is a techno economic model and, thus, excels at depicting economic decisions and interactions of the technical energy system. In contrast, socio-economic impacts lack consideration in almost all of the presented papers, only being considered to a certain degree in Chapter 2. Furthermore, behavioural aspects which can be observed especially in the transportation sector (but also in the buildings sector to some degree) are not represented adequately and would require different modeling techniques or a significant increase in complexity.

1.7.2 Research outlook

Although this dissertation marks the final stage of my current academic training, at least for the time being, there are plenty opportunities to build upon the work presented in the future. As an energy system modeler, there is always something you want to improve on your model code, the data foundation or apply your model in different case-studies. This is even more so the case in this specific instance, since I have been creating, developing, and working with GENeSYS-MOD for the past six years now. The following sections briefly outline some areas where further development is either already planned or could provide valuable insights.

Improvement of usability of GENeSYS-MOD

The first point on this list regards the usability of GENeSYS-MOD, not only for the developers but more so for other people interesting in working with the framework. Section 1.2.4 highlights the need for open science which, apart from providing physical access to source code, data, and publications, ideally also includes easy access to the methods applied. In this regard, GENeSYS-MOD could still be improved, namely in the aspects of programming language and user-friendliness.

To this day, GENeSYS-MOD is written in the General Algebraic Modeling System (GAMS), a language created for the purpose of writing all sorts of mathematical models. However, GAMS requires commercial solver licenses if non-trivial optimization models (i.e., any realistic energy system model) should be run. This fact stands in the way of the accessibility of the methods used, since other people interested in replicating and building upon the results first need to purchase the necessary solvers. Until now only limited examples of applications by people other than the original developers exist, like various master theses (Sørbye and Weisz 2021) or in the case of research projects under guidance by the developers (Berendes et al. 2022). Current efforts examine possibilities of converting the model code or at least data processing to other programming languages like *python* or *julia* but will require major efforts and further optimization.

Another possibility for further improvement of the framework to merge all regional case-studies conducted so far and develop a revamped global version of the model (staying true to its name). Within this global model, users can ideally chose on various levels of disaggregation, with the model clustering the data to fit the user's demands. For example, the modeler could chose to use continents as single nodes but then use higher degrees of detail for China and India while. Providing this functionality could help bring other people to use the model while at the same time improving on the regional and global interactions in the energy system.

Inclusion of socio-economic and behavioural factors

Traditionally, energy system models focus on the technical aspects of the energy system, disregarding or at least undervaluing the inclusion of socio-economic factors in their models. The same holds true for behavioural aspects which, as argued by Huckebrink and Bertsch (2021), usually come with the greatest challenges in these socio-technical transformations. In recent years, improvements within this area could be observed, yet consideration of socio-economic factors in energy system modeling is far from the norm (Krumm, Süsser, and Blechinger 2022). Social aspects are mostly considered as exogenous assumptions during the scenario generation process but seldom included directly into the model structure. These factors include consumer behaviour and lifestyle, social drivers and barriers of innovation diffusion, or public acceptance and opposition (Krumm, Süsser, and Blechinger 2022; Süsser 2020).

As outlined briefly in Chapter 2, an employment module was added to GENeSYS-MOD in the past to analyze the effects of energy transitions on employment numbers (Hanto et al. 2021a). However, more effort is required to adequately represent the social dimension within GENeSYS-MOD. Two concrete examples are the aspects of sufficiency and consumer behaviour. Sufficiency is a concept which recently gained in popularity, focusing on the effects and possibilities which come with a reduced consumption of energy, transportation, or economic goods. It has been integrated in various modeling exercises and has shown to potentially have massive effects on the overall success of the energy system transformation (Kost et al. 2021; Cordroch, Hilpert, and Wiese 2022). A possibility to account for behavioural aspects in energy system modeling comes, for example, with the aspect of modal choice in the transportation sector. The decision of which mode of transportation is chosen rarely based on economic factors alone (Tattini, Gargiulo, and Karlsson 2018). Therefore, including these aspects could improve the representation of the transportation sector in energy system models, although past efforts increased the computational complexity of the models significantly (Tattini et al. 2018; Ramea et al. 2018).

Model coupling

With energy system models specializing more and more on aspect of the energy system, questions arise about the compatibility of their results compared to models highlighting different areas. For example, GENeSYS-MOD has high techno-economic detail but the results are heavily influenced by assumptions regarding prices of fossil fuels (see Chapters 6 and 7). Macroeconomic models, in turn, are good at determining future price developments on global resource markets but lack in technological detail. Immediately, the question has to be asked if it would be possible to combine these two approaches, benefiting from their strengths while eliminating their weaknesses simultaneously.

This question leads to the concept of model coupling, where two or more models with different approaches are used together for an integrated analysis. Integrated assessment models (IAMs) are an already existing form of such a coupling, consisting typically of a combination of bottom-up optimization model and a top-down equilibrium model. While the degree of detail of the single parts is, naturally, lower than of their pure form counterparts, IAMs come with the advantage of considering the interactions between both types. Examples of existing IAMs are MESSAGE (Huppmann et al. 2019) or GCAM.[4]

Apart from this integrated application of model coupling (*hard coupling*), another form exist commonly referred to as *soft coupling*. It describes an approach where model output from one model can be used as input for another model (and sometimes also vice-versa), allowing for an iterative approach where results are transmitted back and forth until convergence in the results is achieved. While the latter is not guaranteed, *soft coupling* still allows to add robustness to the results without compromising model complexity to the degree hard coupling does. Plans for such applications with GENeSYS-MOD are already in progress, with global market models and regional transmission models being ideal candidates for such an exercise.

Adaptation to new trends

Lastly, research and researchers have to adapt to new trends and upcoming challenges. Only a couple of years ago, the field of 100% renewable energies was in its infancy as showcased by Breyer et al. (2022). My own anecdotal evidence proves the point in that on the first conference I attended, the 2016 *Transatlantic Infraday (TAI)* in Washington D.C., I got the perception that people were rather interested in our data assumptions and results on (shale) oil and gas than in the outcomes of a study analyzing a global energy system based on 100% renewables. Today, however, over 100 peer-reviewed articles are published annually and numbers are increasing.

The global energy transition requires a monumental effort and much is left to analyze in the field of energy system modeling. What are the interactions between a global economy,

[4]For further information, see: http://jgcri.github.io/gcam-doc/

rapidly growing population, and an energy system which has to be transformed significantly? Which technological, societal, and political developments are necessary to facilitate this transformation? What is the role of hydrogen? Will we be able to keep global warming in check? By asking and (hopefully) answering these and many other questions, I want to contribute as best as I can to the scientific and public debate in the years to come, following the motto by Brian Grazer in his Book *A Curious Mind: The Secret to a Bigger Life*:

"Curiosity - asking questions - isn't just a way of understanding the world. It's a way of changing it."

Part I

EUROPEAN ENERGY SYSTEM SCENARIOS FOR 100% RENEWABLE ENERGIES

Chapter 2

Lessons from modeling 100% renewable scenarios using GENeSYS-MOD

2.1 Introduction

2.1.1 The origin of 100% renewable scenarios

As a means to combat climate change and stop global warming, scenarios with increasing shares of renewable energy have observed increasing attention with the beginning of the 21st century. When the first scenarios with 100% renewable energy supply were published, back in the 2000 years[1], they were generally considered as "out-of-the-box" thinking, if not completely utopic. This is highlighted by the scientific debate started by Jacobson et al. (2015).[2] They presented an energy system purely based on wind, water, and solar for the United States and thus showing that a low-cost, reliable, renewable energy system is possible. Their results and assumptions were then highly criticized by Bistline and Blanford (2016) as well as Clack et al. (2017). In the following discussion, the team of Jacobson et al. presented a substantial rebuttal to their critics (compare Jacobson et al. (2016) and Jacobson, Delucchi, Cameron, et al. (2017)), but the discussion about the feasibility of 100% renewable energy systems is still ongoing. Loftus et al. (2015) criticize that most scenarios that exclude nuclear or carbon capture technologies need to be supplemented by more detailed analyzes realistically addressing the key constraints on energy system transformation to provide helpful policy guidance. With more studies presenting possibilities of 100% renewable energy systems for different global regions, Heard et al. (2017) presented four criteria for assessing the feasibility of 100% scenarios. They conclude that for all of the 100% analyzes feasibility has been insufficiently demonstrated. Contrary, this approach

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[1] Although the first study on 100% renewable scenarios has been published by Sorensen in 1975 (Sorensen 1975), only from 2009 onward, the number of 100% renewable studies increases substantially (Hansen, Breyer, and Lund 2019)

[2] Although the actual scientific debate started with this article, the most cited article in the field of 100% renewable scenarios is presented by Jacobson and Delucchi (2011)

and result was again highly criticized by Brown et al. (2018). They, on the one hand, address all the concerns raised by Heard et al. (2017), and, furthermore, provide even further evidence for the feasibility of purely renewable based energy systems. Diesendorf and Elliston (2018), in a similar manner, elaborate on the feasibility of renewables providing the key requirements of reliability, security and affordability. They, on the other hand, identify political, institutional and cultural obstacles as main barriers for a 100% renewable system.

Not only the actual feasibility of a 100% renewable energy system, but also the economic and financial perspective, most notably the cost of capital, is a point of discussion. With their study, Bogdanov et al. (2019) presented a sophisticated assessment of a globally 100% renewable power system. Here, they were criticized by Egli, Steffen, and Schmidt (2019) for using globally uniform cost of capital assumptions, as they argue that these assumptions may result in distorted results and policy implications. This rebuttal was answered by Bogdanov, Child, and Breyer (2019), who agree with some points, but also highlight flaws in the rebuttal by Egli, Steffen, and Schmidt (2019).

Overall, the discussion of 100% renewable scenarios shifted from general feasibility issues to specific assumptions. Studies analyzing the transformation of energy systems should also be aware of the biases and correctness of assumptions. Creutzig et al. (2017) show the underestimated potential of solar energy within the fifth assessment report of the IPCC due to underlying bias in the models. Also, as presented by Mohn (2020), the International Energy Agency's (IEA) World Energy Outlook (WEO) suffers from a status-quo bias in favor of fossil fuels and constantly underestimates the potential and development of renewable energy sources. This is especially important, as the WEO is an often-used data source for many energy system scenarios. A further analysis and comparison of different energy outlooks and scenarios is presented by Ansari, Holz, and Al-Kuhlani (2020). By the end of 2019, there are now numerous studies, which elaborate renewable energy scenarios using different models including sector coupling. Jenkins, Luke, and Thernstrom (2018) review and distill insights from 40 papers examining low carbon scenarios since 2014 including various articles showcasing 100% renewable scenarios. An even more comprehensive literature overview of in total 180 academic peer-reviewed papers since 2004 examining 100% renewable pathways can be shown in Hansen, Breyer, and Lund (2019). This is complemented through a recent special issue by the journal Energies comprising of 12 more papers on this topic by Kemfert, Breyer, and Oei (2019). Also, Breyer et al. (2020). examines the techno-economic benefits of global energy interconnection throughout high renewable scenario pathways.

Jacobson, Delucchi, Bauer, et al. (2017), being one of the first elaborate studies, provide an extensive analysis of 100% RES by 2050 of 139 countries. The results show that 100%

RES is possible and can contribute to the (energy price) stability, the decline of unemployment and health related problems due to high pollution, and increase energy access because of decentralized RES. Its findings of the feasibility of a 100% RES scenario in that way supports assumptions made in this paper. Moreover, Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) conduct studies focusing on pathways until 2050 by using the energy system model GENeSYS-MOD and examining case studies (Hainsch et al. (2018); Lawrenz et al. (2018)). Additionally, Ram et al. (2019) find out that a 100% renewable pathway is globally feasible in all analyzed sectors (power, heat, transport and desalination) before 2050 using the Lappeenranta-Lahti University of Technology (LUT) energy system model. They further show that the sustainable energy system is more cost effective and efficient. Therefore, PV is also the main driver in terms of employment in the job calculation based on Ram, Aghahosseini, and Breyer (2020).

Various of the mentioned papers are focusing on both the economic dimension and the climate and energy dimension. This underlines the importance of this topic and deserves a thorough investigation.

2.1.2 Research focus

This paper showcases specific characteristics and challenges for energy system modeling of 100% renewable scenarios. The findings are based on various applications and modifications of the framework GENeSYS-MOD examining different regional characteristics for high renewable configurations. The main aim of models has never been to provide numbers, but insights (Huntington, Weyant, and Sweeney 1982) - still challenges prevail for modelers to use the best configuration of their models to actually provide helpful insights. This becomes even more complicated due to increasing complexity of the energy system transition through the potential and need for sector coupling as well as rising international connections. The following sections therefore elaborate on our experiences of the last years of choosing the best, yet still computable, configuration of GENeSYS-MOD (Section 2.2) with respect to spatial (Section 2.3) and temporal resolution (Section 2.4) as well as sufficient detailed description of the energy system transition effects (Section 2.5) and result interpretation (Section 2.6). The aim of this paper is therefore twofold, to better understand and interpret existing models as well as to improve future modeling exercises.In doing so, it tries to answer the following research questions: (i) "What key lessons did we learn from modeling energy systems based on 100% renewables?" and (ii) "What are best practices and areas for improvement in the field?".

2.2 Methodology

2.2.1 Description of the Global Energy System Model (GENeSYS-MOD)

The Global Energy System Model (GENeSYS-MOD) is based on the well-established Open Source Energy Modelling System (OSeMOSYS), an open-source software for longterm energy system analyzes. OSeMOSYS is continually developed by a number of researchers worldwide in a decentralized manner and is used in countless scientific and policy advisory publications. Based on this model, GENeSYS-MOD was developed for the present analyzes. The objective function of the model covers the total cost of providing energy for the electricity, transport, heating, and several industrial sectors in a predefined region (compare Figure 2.1). The model result is a cost-minimal combination of technologies to fully meet energy demand at all times. Climate targets, such as a CO_2 emissions budget, are explicitly specified as a condition for the model calculations. The CO_2 budget set for a region is based on the remaining global budget to meet the Paris climate change targets of maximum warming of less than two degrees Celsius. The global budget is hereby broken down to regional shares based on population figures of 2015.

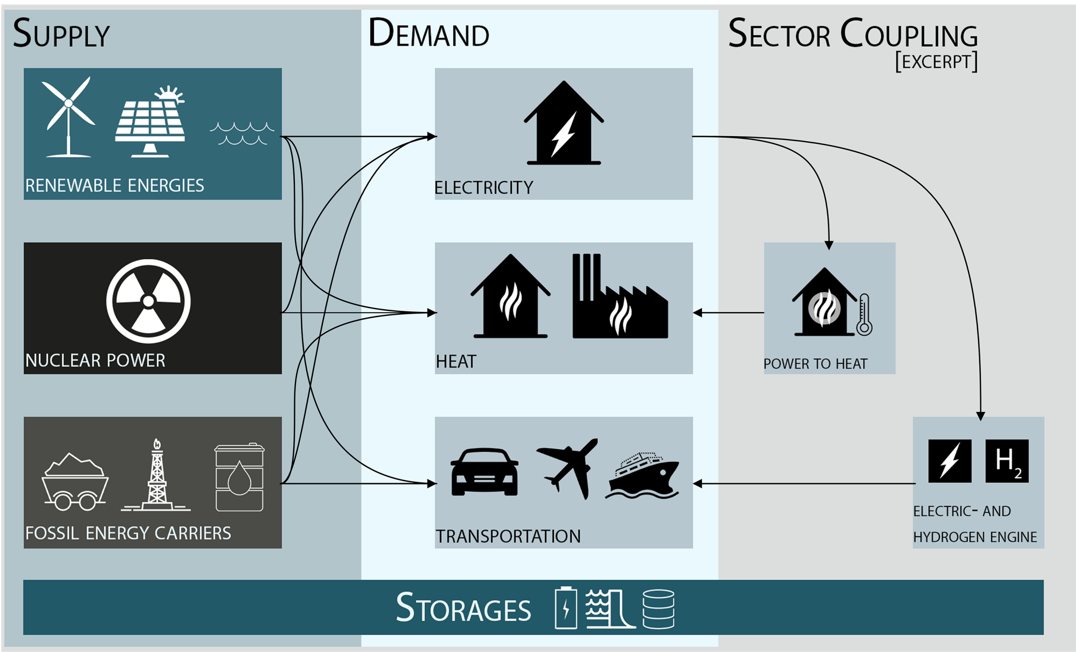


Figure 2.1: Description of GENeSYS-MOD. Source: Own depiction based on Löffler, Hainsch, Burandt, Oei, and Hirschhausen (2017).

2.2.2 Data assumptions

Since the availability of wind and solar energy fluctuates with the weather conditions, a temporal and spatial balance is necessary in order to be able to cover the energy demand at any time. For this purpose, several technologies for storage and sector coupling are implemented in the model. Above all, lithium-ion batteries serve to balance temporal fluctuations in energy supply and demand. In addition, the coupling of the electricity sector with the transportation, heating and industrial sectors enables their decarbonization by using electricity from renewable sources. Spatially, the model in most applications comprises of 10-20 nodes, grouping together a number of smaller countries or regions. It is possible to exchange fuels and electricity between the regions, but not heat. In order to keep the complexity of the model calculable, aggregation is also carried out on a temporal level. In the course of the analysis, all hours of a year are summarized into time slices, which represent seasonal and daily fluctuations of demand and the availability of renewable energies.[3] The years 2020 to 2050 are considered in integrated five-year steps, assuming full knowledge of future developments in demand, costs, and availability of renewable energies. The calculations are mainly based on cost estimates from 2018; however, the results could underestimate the potential of renewables due to unexpected, rapid cost decreases in renewable energies as well as storage technologies. On the other hand, the calculations do not sufficiently consider a part of the integration costs of renewables due to the lower regional and temporal resolution, which leads to an overestimation of the potentials of fluctuating renewables.

The underlying cost assumptions can be found within an overall data documentation of GENeSYS-MOD (Burandt, Löffler, and Hainsch 2018). Country specific data is specified within the respective papers analyzing the world (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017), China (Burandt et al. 2019), Europe (Löffler et al. 2019), Germany (Bartholdsen et al. 2019), India (Lawrenz et al. 2018), Mexico (Sarmiento et al. 2019), South-Africa (Hanto et al. 2021b) and Colombia (Hanto et al. 2019).

[3] The results are based on model runs with a different amount of time slices varying from 6-120 time slices per year.

2.3 Choosing the best spatial resolution

2.3.1 The devil lies within the detail: differences of a continental, national and regional Investigation

The devil lies within the detail as can be seen in our application of the framework GENeSYS-MOD to analyze 100% renewable pathways for the world (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017), Europe (Löffler et al. 2019), and Germany (Bartholdsen et al. 2019) (see Figure 2.2). This becomes particularly apparent, when examining the distribution of different renewable technologies. The global analysis shows an even spread of wind on- and offshore and photovoltaics. A more detailed look at the European level, however, clarifies that some countries - mostly within Southern Europe - focus on photovoltaics. More northern countries, on the other hand, profit from high wind energy potential. Also, when looking in more detail at the evolvement over time, some countries - e.g., Poland - envision a much slower progress compared to other countries. This can be explained by very low starting values of renewables in 2015, which need more time to ramp up to high renewable shares in later periods. While these results might not be of big surprise to experts of the European energy system - they, however, explain the need for calibrating less spatially detailed linear models in a sufficient matter: a linear global model might otherwise choose to only invest in the cheapest renewable technology for each continent, not incorporating regional differences. Such model outcomes would in this case result in too simplified answers with little to no real insights. This can also be seen in papers by Horsch and Brown (2017), Cao, Metzdorf, and Birbalta (2018) and Hess, Wetzel, and Cao (2018) examining the role of spatial scale in joint optimizations of generation and transmission. They show trade-offs between better representation of transmission or distribution grid representation, exploitation of renewable sites and computational limitations for highly renewable scenarios.

Also, increasing the regional detail even further - looking at federal regions within Germany - it can be seen that some city states, e.g., Berlin, do not have sufficient space to produce renewable capacities. Such regions are depending on renewable capacities and energy trade from neighboring regions —an aspect which would not become visible only using lower resolution model applications. A similar but even more extreme effect of energy trade between even changing load centers will be analyzed in the following section.

2.3.2 The energy transition can result in the shift of energy supply centers

A regional disparity in the availability of energy sources and demand centers is observable in many countries. This has led to the construction of transmission lines connecting demand centers with central energy production regions, which were often in the proximity of fossil reserves (e.g., coal mines) or international fossil fuel trading infrastructure (e.g., terminals or pipelines). These energy production regions, however, in some cases are about to change as renewable potential sites might be located in different regions.

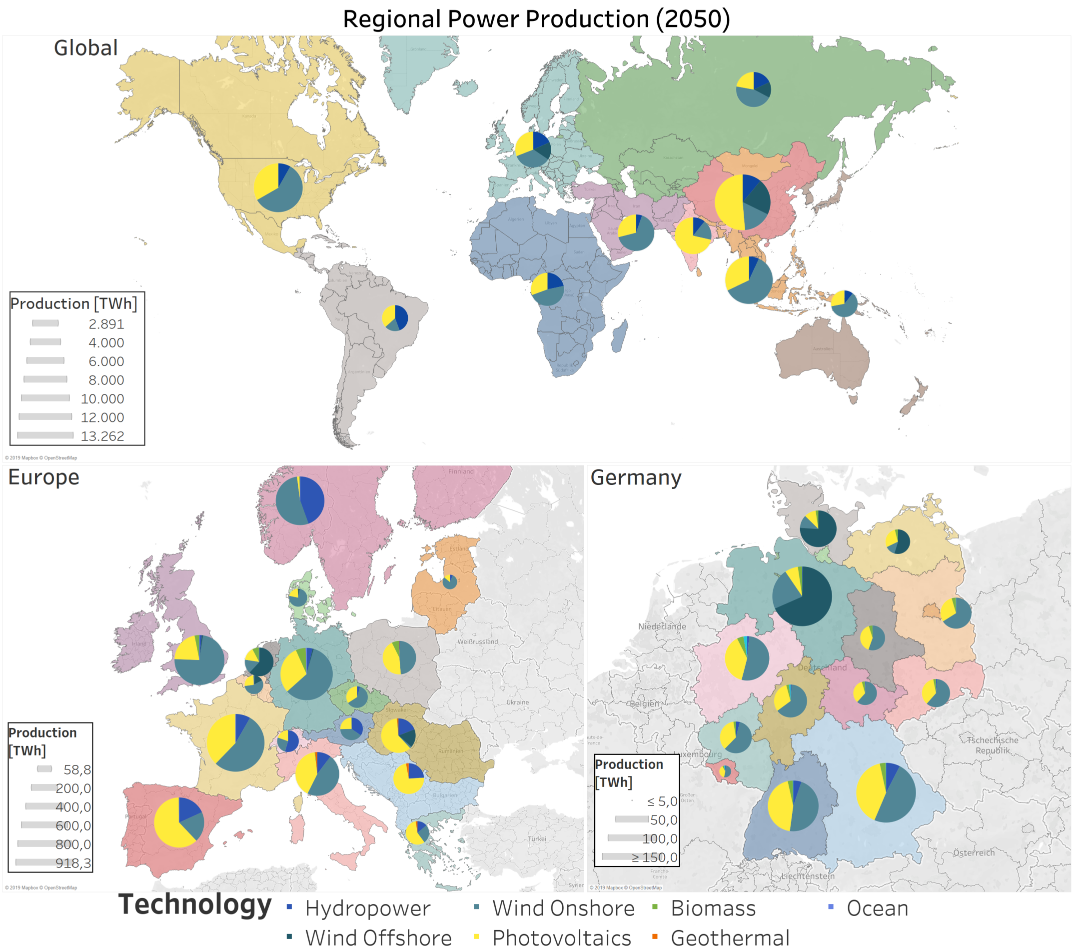


Figure 2.2: Scaling down 100% Renewable scenarios - for the World, Europe and Germany. Source: Own illustration based on Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017), Löffler et al. (2019), and Bartholdsen et al. (2019).

Extreme examples for this were examined by us within South Africa (Hanto et al. 2021b) and China (Burandt et al. 2019). In South-Africa, in 2015 coal mining as well as the production of electricity concentrates in Mpumalanga as illustrated in Figure 2.3. Within a high renewable scenario by 2050 this role of the biggest power producers shifts to regions like Northern Cape, Eastern Cape, and Free State (Hanto et al. 2021b). Similar results can be seen within the case study on China (Burandt et al. 2019): Being a region with high solar irradiation, Inner Mongolia will become the dominant power-generating province in China. This will require substantial grid extension measures (nearly doubling the total power transmission capacity from 2020 until 2050). On a positive note, the large regional extension of China enables the regional power trade to balance out the variability of renewables. Also, the regional disparity in the availability of biomass results in a significant increase in biomass, hydrogen, biogas, and synthetic methane trading. Such configurations are presented as cost-optimal from a central omniscient planners' perspective. The implied needed investment costs for the electricity transmission and distribution grid (Breyer et al. 2020), however, underestimate difficulties and transaction costs for the construction of such enormous infrastructure within such short time and therefore deserve further research. Incorporating additional transaction costs, e.g., to increase public acceptance for the construction of new transmission lines, or including local preferences for keeping existing power production centers, might instead result in more realistic projections.

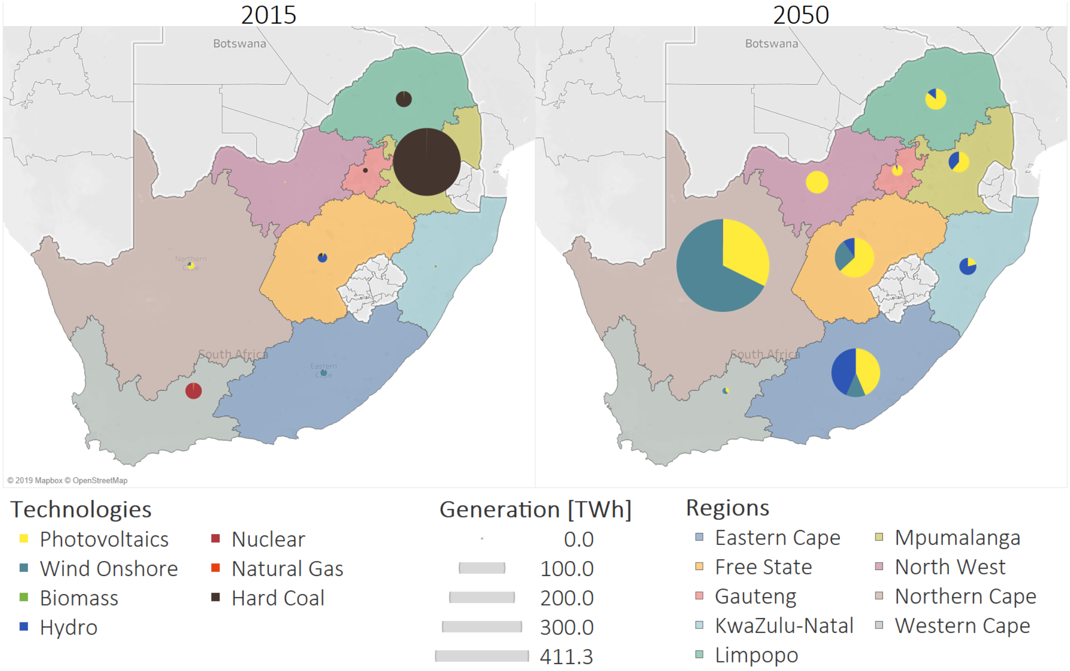


Figure 2.3: Change of regional power production in South Africa. Source: Own illustration.

2.4 Temporal aspects of modeling

2.4.1 Improving the time resolution

Increasing the time resolution of model runs enables scenarios to replicate seasonality as well as inner daily differences of energy supply and demand. Incorporating seasonal differences has always been of importance, especially for countries with a high difference in temperature, e.g., European summers and winters. When analyzing high renewable scenarios, also other seasonal elements become of even higher importance, e.g., the monsoon in India. The Indian monsoon results in high wind speed in the western Indian peninsula in the months from march to august making it relatively easy to imagine a renewable-based energy system for these months. Alternative energy sources or long-term storage options, however, are needed to enable a 100 % renewable energy supply throughout the year (Gulagi, Bogdanov, and Breyer 2017; Lawrenz et al. 2018). Additional research will be needed to investigate the direct effect of climate change on energy production (i.a., changing weather patterns, changing hydropower production, water scarcity for cooling of fossil units).

The effect of applying different time resolutions can be seen within sensitivity runs of our case study on China, see Burandt et al. (2019). We analyze decarbonization pathways of the Chinese energy system comparing different hourly resolutions. The sensitivity scenario calculating every 73$^{\text{rd}}$ hour with ramping constraints was used as a baseline. As shown in this Figure 2.4, the reduction from every 73$^{\text{rd}}$ to every 25$^{\text{th}}$ hour for the selection of the final time-series does not significantly impact the results, especially in the first years of the modeled periods. Deactivation or activation of the newly added ramping equations (compare Burandt et al. (2019) for a detailed description of the equations), on the other hand, has a bigger influence on the results. For the annual power production, a decrease of natural-gas usage in the later model periods can be observed when the ramping constraints are deactivated. Also, removing these constraints leads to a prolonged relevance of coal in the power system. Without ramping constraints, coal can be used in the model as a flexible power generation to balance intermittent variable renewable energy sources alongside storages, although coal-fired power plants often have only limited cycling and ramping capabilities in the real world.

This shows that additional ramping constraints can help to produce more realistic results with fewer jumps of different technology usages. Choosing the right set of time resolution, on the other hand, appears therefore of lesser importance. This is in line with similar research by Welsch et al. (2014) and Poncelet et al. (2016), on the other hand, conclude that temporal detail should be prioritized over operational detail; which is also in line with findings of Haydt et al. (2011). Kotzur et al. (2018a, 2018b) find the impact of the aggregation level to have a significant reduction in the computational load, but to be highly system-specific and not generalizable with respect to the results. One reason for our results of limited temporal differentiation with GENeSYS-MOD is our dominating assumption of perfect foresight of an omniscient planner. The following section will, therefore, present findings from implementing limited foresight into the model.

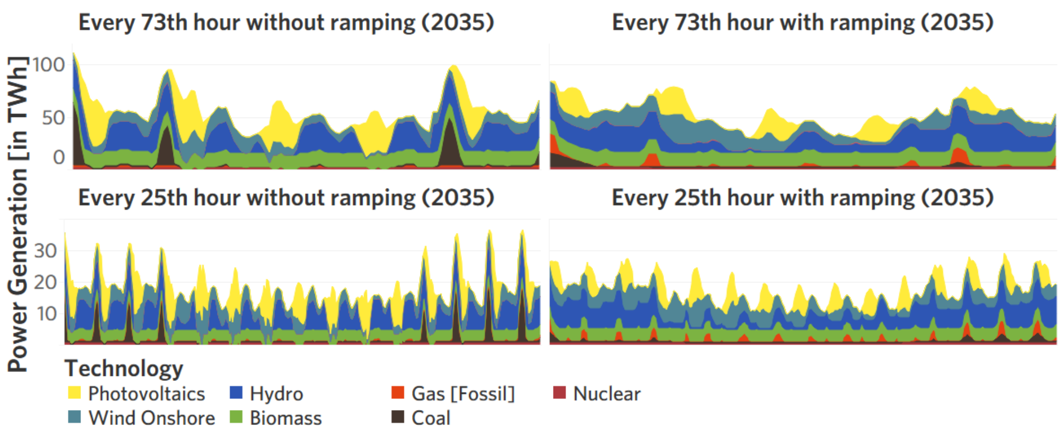


Figure 2.4: Effects of more detailed temporal resolution in comparison to better technical representation of ramping. Source: Adapted from Burandt et al. (2019)

2.4.2 Effects of reduced foresight on energy pathways

One crucial feature of most large-scale energy system models is that they operate under the assumption of perfect foresight. This is valid both for intra-year data (see Section 2.4.1), as well as for the pathway computation. The model therefore already "knows" about all impacts and costs that would occur for each possible decision and tends to choose the cost-optimal pathway from the viewpoint of an omniscient social planner.

While this assumption of perfect foresight is useful for most analyzes, it does not quite reflect the actual behavior of interested parties. For example, both politicians or companies might have a more limited time horizon in mind (e.g., thinking of election periods or short-term profitability goals of companies), focusing more on short-term gains, instead of long-term benefits. This holds especially true for energy pathways and climate protection - since these usually require long-term investments that cause path dependencies, but incumbent actors and policy makers might focus more on approval ratings with voters, or keeping their business going as long as possible (e.g., in the case of the coal industry). It can thus be assumed that when prioritizing these short-term gains, climate action will be delayed and hinder a potential achievement of current targets - being in contradiction with principles of inter-generational justice.

Löffler et al. (2019) analyze this discrepancy between theoretical socially cost-optimal pathways and those, that would occur when foresight into future action is limited. For this, they introduce two new scenarios to their European model - both featuring myopic (reduced) foresight. Figure 2.5 shows the differences between the BASE scenario, one including reduced foresight (RED) and one that additionally introduces political boundaries and barriers (POL).

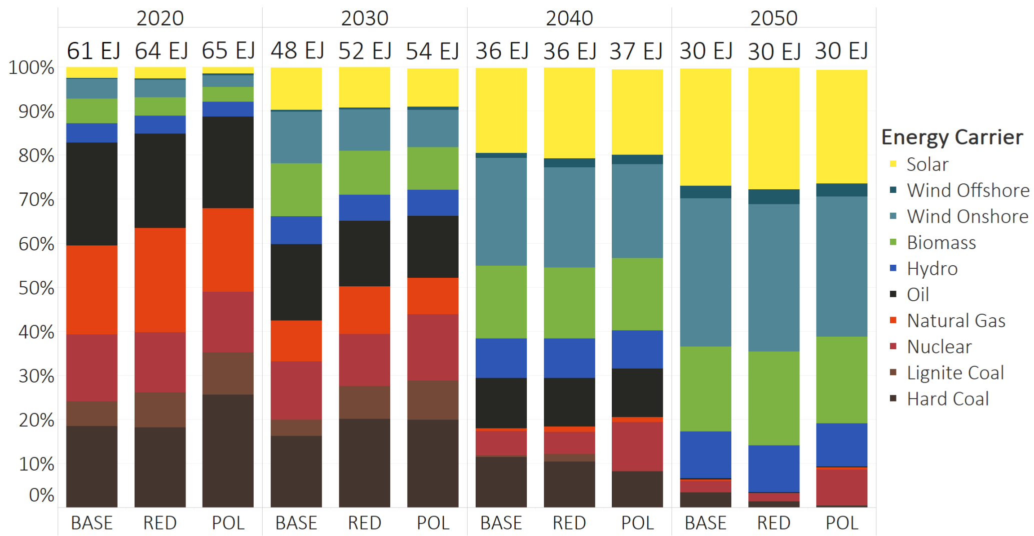


Figure 2.5: Primary energy supply, both relative, as well as total amount in Exajoule (EJ) for Europe. Source: Adapted from Löffler et al. (2019)

Clear differences can be observed: coal-based technologies see an increased use in the near to intermediate future, at the cost of the growth of RES when reduced foresight is included. Interestingly enough though, since all scenarios are required to adhere to the 2°C goal, the RED and POL scenarios actually need a steeper emission reduction path in the later years. This comes with significant cost increases, as well as massive amounts of stranded capacities (see Figure 2.6) and technical challenges for a faster ramp up of some technologies only in the 2040s. Also, such steeper transformations in the 2040s might result in higher societal challenges or even structural breaks endangering the aimed at just transition. Another interesting approach by Heuberger et al. (2017) considers the effect of including endogenous technology cost learning to improve optimal capacity expansion planning.

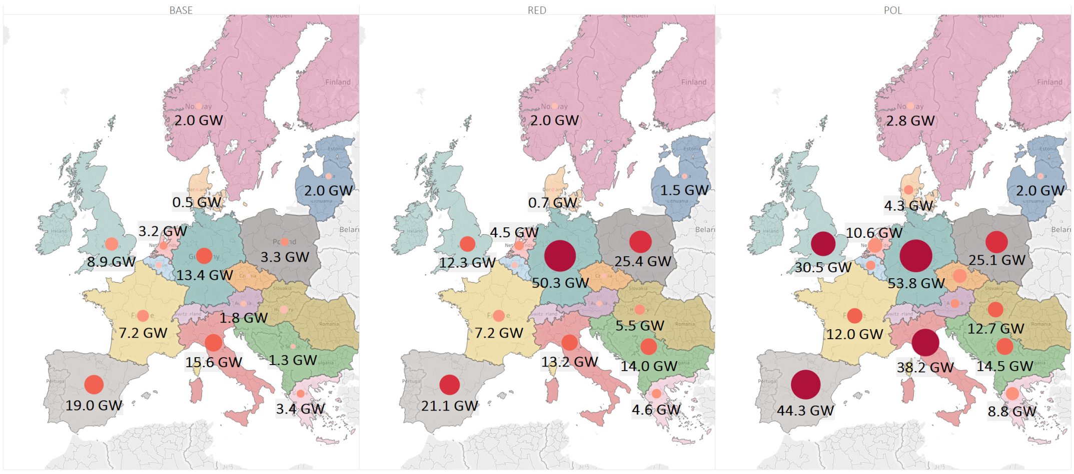


Figure 2.6: Total stranded assets for coal- and gas-fueled power generation in the year 2035 across Europe. Source: Adapted from Löffler et al. (2019).

This demonstrates that in cases where (very) long-term outcomes have to be considered, as in the case of global warming, decisions should focus on long-term feasibility of policies and their effects (such as path dependencies). Clear, strong signals are needed from policy makers to combat the threat of short-sighted investment decisions that would result in stranded assets and more challenging climate action in the future.

2.5 More detailed analysis of sectoral transitions

2.5.1 Examining the industry sector more closely

For assessing the potential impact of sector-coupling on the development of an energy system, a detailed sectoral representation also of the industry sector is needed as seen within works of Lechtenböhmer et al. (2016), Vogl, Åhman, and Nilsson (2018), and Fleiter et al. (2018). Currently, only limited technologies that allow direct electrification of high-temperature industry processes (e.g., steel, aluminum, or cement production) are available or still need fossil feedstock. Therefore, the distinct inclusion of such processes in energy system models is needed for assessing ambitious decarbonization scenarios. Especially for China, whose energy-intense high-temperature industry is of high importance, the explicit representation of different industrial sectors is needed for generating thoughtful insights. Therefore, Burandt et al. (2019) altered the preexisting structure of high-temperature and low-temperature heat, as depicted in Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017)

and Burandt, Löffler, and Hainsch (2018). The new four different temperature ranges with allowing for a more distinct differentiation in industrial (0-100°C, 100-1000°CC, and >1000°C) and residential heating (0-100°C).

Due to higher CO_2 abatement costs, it is only in the 100% renewable scenarios that coal is phased-out also within the industrial heat sector (see Figure 2.7). This phase-out is accompanied by higher usage of gas- and biomass-based heating. In the second quarter of the century, hydrogen and geothermal play a more significant role. Nevertheless, a large degree of electrification is required, which is most cost- and emission-efficient when the power sector is already decarbonized. The examination of an optimal decarbonization share of individual sectors will therefore be examined more closely in the next section.

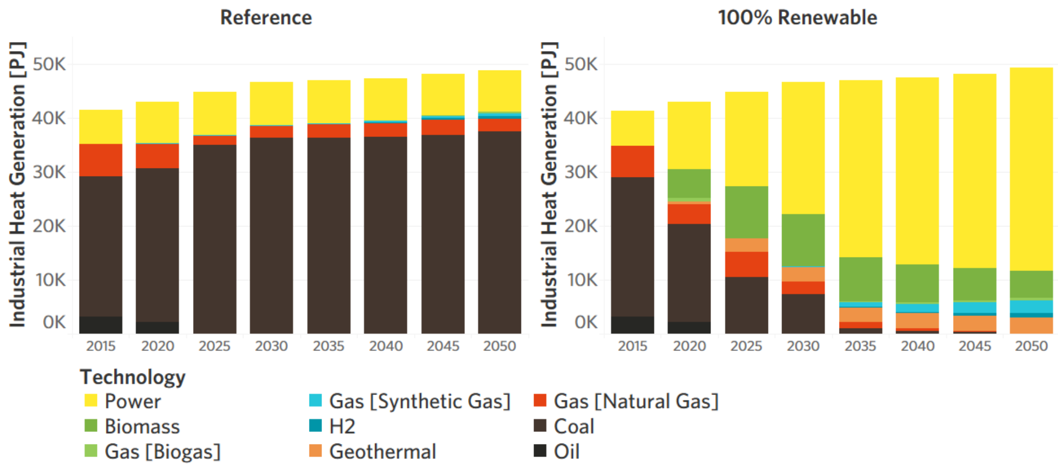


Figure 2.7: Decarbonization of industrial heat in China. Source: Adapted from Burandt et al. (2019).

2.5.2 What is an optimal share of renewables for each sector

A common question of politicians, industry representatives as well as modelers is the one of cost-optimality. Thus, not only determining cost-optimal pathways for certain climate pathways, but also the theoretical optimum when it comes to renewable integration, is of high interest. To tackle this issue, Sarmiento et al. (2019) introduced a new function to GENeSYS-MOD that performs an iterative computation that fixes the amount of renewables for the energy system or selected sectors to a value between 0 and 100%. This is done in 5% steps, always tracking the changes in total system costs.

As a result, a cost curve that represents the relative change in costs can be obtained. This cost curve regularly takes the shape of a ”U” (see Figure 2.8), meaning that the integration of RES into the system first leads to (usually significant) cost savings, whereas towards 100% RES, the costs usually increase again. This is vastly different for the different sectors, with power and transport showing very high cost-optimal shares of renewables (75% and 90%, respectively), whereas the heating sector (especially when it comes to industrial process heat) experiences rather low shares (5% for the Mexican energy system). This is due to the inherent differences between the sectors, concerning the availability of RES-based technology options and their cost assumptions.

When negative externalities, such as environmental damages are considered, the relative competitiveness of RES compared to its (polluting) fossil counterparts, is shifted. The German Environment Agency (UBA) states that the environmental costs of one ton of CO_2 amount to 180€ in 2016 (Matthey and Bünger 2019). When these costs are considered in the computations for the Mexican energy system, the cost-optimal amount of renewables jumps by 10%,

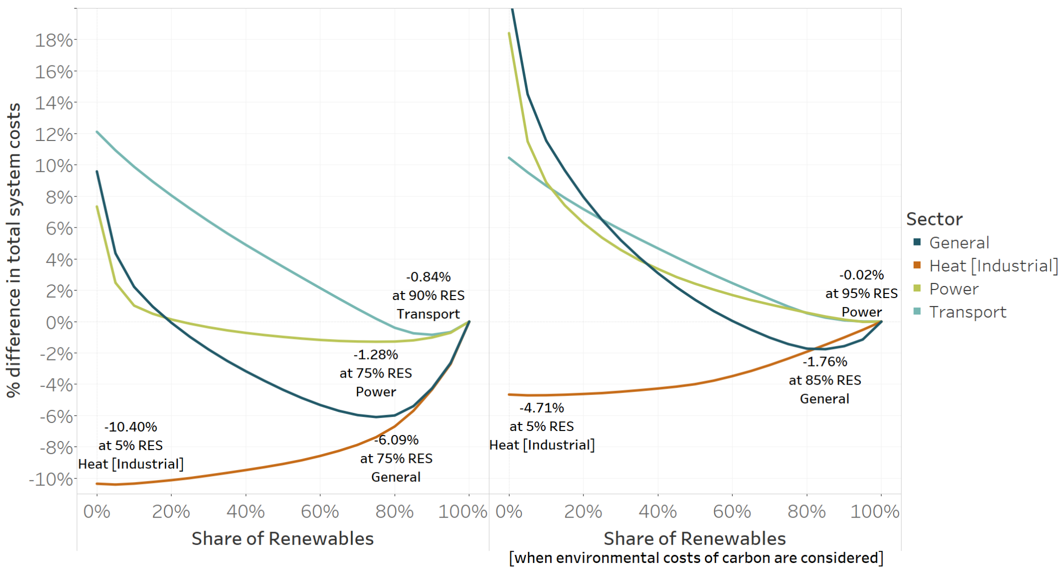


Figure 2.8: Calculating an optimal renewable share for Mexico. Source: Adapted from Sarmiento et al. (2019).

2.5.3 Examining the employment potential of the energy system transition

Energy system models can help political decision makers to understand consequences of the transition not only for the technological energy system but also for the resulting employment effects as elaborated for South-Africa (Hanto et al. 2021b) and Colombia (Hanto et al. 2019) in the following section.

In some countries, a low-carbon transition is particularly important as the coal mining sector is the most significant single energy employer in the energy sector with 130,000 direct jobs in Colombia (Strambo and Atteridge 2018) or 77,000 in the coal mining industry in South-Africa (Minerals Council South Africa 2018). Most of these jobs are located in few locations. The upcoming transition can therefore be seen as a chance, as the build-up of renewables in the country is more equally distributed across the country and could therefore - if managed well - help miners to leave (the sometimes poor working conditions) and find employment in the newly established renewable energy sector. Our model results show that overall national energy employment will see a strong increase in high renewable scenarios. Coal mining jobs, on the other hand, decline dramatically because of fuel switches in the power and heat sector as well as rising automation. This is similar to past development occurring in coal mining in many Organization for Economic Co-operation and Development (OECD) countries in the 1970s-1990s, where total job numbers in coal mining shrank to a fraction of previous levels (Stognief et al. 2019; Oei, Burandt, et al. 2020). In most coal mining countries, regarding the high median age of miners, the decline in jobs would not necessarily be a problem for currently employed people (Oei and Mendelevitch 2019). The next generation of workers, however, needs to be addressed individually, as the continuity of their parent's jobs is not given due to changes in the energy sector, even without a large system transformation to renewables.

Development of renewable energies will generate new employment opportunities along the entire supply chain (López et al. 2020). Job types differ in temporal occurrence as well as possible geographic location. Looking at the skill level, the relatively low needs for expertise in the operation and maintenance (O&M) in the PV sector are ideal to create jobs for former miners. For Colombia, permanent jobs in O&M triple from 2015 until 2050 in total and are mainly due to the build-up in PV power capacity and to a lesser extent due to additional hydropower capacity. Combined with the steadily rising job numbers for the construction and investment (C&I) and partial manufacturing of PV power stations, the total jobs, excluding the manufacturing side, significantly outnumber the coal mining job numbers of 2015 (compare Figure 2.9).

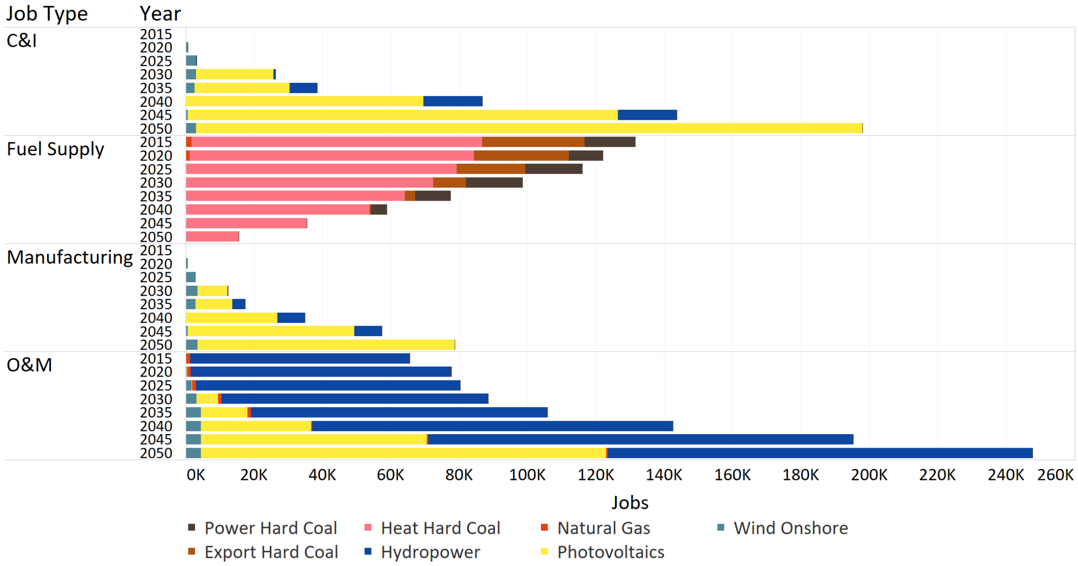


Figure 2.9: Employment effects for 100% renewable scenarios in Colombia. Source: Adapted from Hanto et al. (2021b).

2.6 Conclusion

This paper underlines the importance of a fast renewable application to slow down global warming and to prevent a climate catastrophe. This transition, at the same time, goes along with the possibility of creating new jobs and providing electricity access to many regions in the world. Relying on the existing mathematical models to calculate such optimal configurations of more sustainable pathways and technologies choices, however, go along with several model(er)'s biases, elaborated in more detail in the following:

- Models largely depend on taken assumptions, including in particular the choice of data, sometimes having to be estimated far into the future. Applying discount factors for future costs and damages, as done by most models, hereby contradicts any principle of inter-generational justice concepts. Using a social discount rate instead, might provide different results for many modeling exercises.
- Some elements or values are difficult or impossible to quantify and therefore mostly neglected within models. Examples for this are, e.g., externalities such as the cost/value of destroyed nature, natural heritage, culture or happiness. Making such shortcomings explicit within modeling tasks would help to clarify the (in-)adequacies of mathematical models.

- Models include a variety of endogenous technology choices from renewables, nuclear, to various negative-emission-technologies (NET) to meet the mostly exogenous energy demand. NET, however, as seen from the past experiences of carbon capture technologies (C. v. Hirschhausen, Herold, and Oei 2012; Oei, Herold, and Mendelevitch 2014; Oei and Mendelevitch 2016), are unlikely to provide sufficient CO_2 mitigation potential. Not incorporating different behavioral (as well as technical) options to endogenously reduce overall energy demand or even change the entire economic system, however, is limiting our analysis to a narrowed scenario-cone which all imply a continuation of the existing societal system without any radical systematic changes (Vuuren et al. 2018; Braunger and Hauenstein 2020). Interdisciplinary exchange and possible (soft) linkage with behavioral models could be a first step to address this issue.
- Underlying model assumptions of technical (i.a., regarding foresight, actor behavior or data) or more systematic nature (economic and societal - mostly European or American - context) will never be able to predict the reality. It is therefore important to clearly state these assumptions to put the results into a context, especially when examining regions within the Global South. Interactions with (local) practitioners to discuss the outcomes can help to assess such shortcomings and should be used to improve future runs.

Being aware of these model(er)'s biases can help to improve future modeling work allowing for a better interpretation of the still helpful insights that energy system models can provide. Even though many uncertainties of the future energy system prevail and regional challenges differ a lot; still some general no regret options can be identified from our experiences:

1. Reduce energy demand through the enhancement of behavioral changes as well as technological improvements such as efficiency gains. Also, the recycling and more efficient usage of resources is essential to limit negative effects on society, environment, and nature.
2. Investment in renewables enables the energy system transition and provides numerous job opportunities for people around the globe. By the end of 2018, already more than 11 million people are employed within the global renewable sector (IRENA 2019).
3. Avoid additional investments in fossil fuel infrastructure (i.a., mines, oil rigs, harbor terminals, gas pipelines) which might otherwise create lock-in effects as well as potential sunk investments. By 2020, no new infrastructure should be constructed which is not compatible with a zero carbon society.
4. Weaken the fossil fuel regime and support alternative actors to ease a faster transition to more sustainable energy forms. The shrinking remaining CO_2-budget alarms us to fasten the upcoming energy transition unprecedented compared to other historic

industrial transition. This societal challenge will therefore only be possible if sufficient actors agree to join this pathway to a more sustainable, just, and in-time transition.

Further inter- and trans-disciplinary research is needed to accompany the upcoming energy system transition. From a modeling perspective this could be achieved through the (soft) coupling of energy system models with other models examining macro-economic effects (e.g., CGE-models) or behavioral aspects (esp. within the transport sector). However, also more qualitative works, e.g., on the political economy of fossil fuel phase-out, could be included in models through the inclusion of regional specific transition indicators. In addition, the effect of the energy system transition on the energy-food-nexus, the usage of rare earth materials or on other sustainable development goals would be of high interest for academia and society likewise.

Chapter 3

Review and comparison of European energy transition scenarios

3.1 Introduction

In December 2019, the European Commission (EC) released their plans for tackling climate and environmental-related challenges - the European Green Deal (EGD) (European Commission 2019c). As a response to climate change, environmental risks and pollution of forests and oceans, it ”aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 [...]” (European Commission 2019c).

This pledge for carbon neutrality and commitment to the Paris Agreement by the European Commission comes at a time where decarbonization pathways and the question of how to reach net-zero GHG emissions by the mid of this century is extensively being analyzed by research and governmental institutions. Prominent examples are the IPCC Special Report on 1.5°C (IPCC 2018), multiple studies by the EC (European Commission 2018b, 2020b; Nijs et al. 2018) but also from non governmental research institutions like from the Wuppertal Institut (Kobiela et al. 2020), the Öko Institut (F. C. Matthes et al. 2018) or by CLIMACT and ECF (2018).

Most of these studies combine, at least, two different methodologies, those being the fields of energy system modelling and scenario analysis. On the one hand, energy system modelling, while initially originating from energy security and cost concerns, is nowadays mainly motivated by climate change policies and the need for significant GHG reduction targets (Meinshausen et al. 2009; Pfenninger, Hawkes, and Keirstead 2014). The interpretation of results generated by energy system models can be challenging and misleading at times, especially if raw numbers are seen as the outcome of a model (Wiese, Hilpert, et al. 2018). On the other hand, scenario development and analysis proves to be the predominant way

This chapter is based joint work with Konstantin Löffler, Thorsten Burandt, Hans Auer, Pedro Crespo del Granado, Paolo Pisciella, and Sebastian Zwickl-Bernhard published in *Energy* (239, Vol. C) under the title: ”Energy Transition Scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal?” https://doi.org/10.1016/j.energy.2021.122067; published open access under CC BY 4.0.

of using energy system models. Scenarios, and more specifically the relative differences between various scenario results, can help with the communication at the modeller/policy interface by highlighting the insights which can be deduced from model results (Strachan, Fais, and Daly 2016; Wiese, Hilpert, et al. 2018).

In the case of the European energy transition, a large number of studies and projects are dedicated on decarbonization pathways which will be discussed more in-depth in Chapter 3.2. One such project is the openENTRANCE project, which ”aims at developing, using and disseminating an open, transparent and integrated modelling platform for assessing low-carbon transition pathways in Europe.”[1] As one part of the project, four different scenarios are defined using a novel scenario generation process and results for the pan-European energy transition are computed with the help of the GENeSYS-MOD for each of the four scenarios (Auer et al. 2020). Since similar exercises were also conducted by other researchers and governmental institutions, the question remains if general observations and results can be found across all studies which, in turn, would help significantly in identifying policy recommendations, possible uncertainties and no-regret options.

Therefore, the contribution of this paper is threefold: First, an extensive review of European energy transition pathways considering high GHG emission reduction targets for 2050 is conducted which highlights the current landscape of decarbonization scenarios (Chapter 3.2). Second, a novel scenario development process based on a three-dimensional approach is introduced along with a brief discussion of the results of the openENTRANCE pathways (Chapter 3.3). Lastly, these results are mirrored against similar other pathways which analyze European decarbonization scenarios to determine common findings and recommendations which are then, in a second step, highlighted in the context of the European Green Deal (Chapters 3.4 and 3.5).

3.2 Review of European Energy transition Pathways

Assumed decarbonization targets and the socio-political and techno-economic context greatly influence pathway perspectives and their main narratives. In this regard, multiple scenario and pathways studies focus on a global, continental or country wise perspectives and their respective energy transition challenges. This chapter presents a review on existing work on defining and analyzing scenarios focused on the European energy transition.

[1] More information about the openENTRANCE project can be found under: https://openentrance.eu/

3.2.1 European Commission scenarios

The European Commission Directorate-General for Energy (DG ENER) conducts its own impact assessment studies which, at times, come along with policy packages for institutions of the EU. These impact assessments are usually quantitative based analyses which are used to include key visions on possible scenarios to support the definition of policies. In the last years, the European Commission has conducted three main impact assessment studies, outlining key challenges associated with achieving the decarbonization targets declared by the EU through an analysis of policy and technology scenarios which will be summarized in the following paragraphs.

Energy Roadmap 2050 scenarios

These scenarios focus on sustainability, competitiveness and security of the EU energy system (European Commission, DG-ENER 2012). The main drivers and decarbonization routes noted in the *Energy Roadmap* are built around four key technological developments: energy efficiency, renewable energy, nuclear energy and carbon capture and storage, which form a roadmap consisting of seven energy transition scenarios until 2050. These scenarios include assumptions on a wide portfolio of technologies, the role of consumers and investors and outlooks of existing regulatory frameworks.

Clean Energy for all Europeans package

The objective and scope of the *Clean Energy for all Europeans* scenarios is to analyze the feasibility of the 2030 climate targets. The scenarios mainly envision a decarbonization compatible with the 2°C climate target by modelling "[...] the achievement of the 2030 climate and energy targets as agreed by the European Council in 2014 (the first scenario with a 27% energy efficiency target and the second with a 30% energy efficiency target)" (Capros et al. 2018). With the EU reference scenario as a starting point, the following, more ambitious, *EUCO scenarios* aim to assess a very specific range of climate and energy targets, those being: (i) reduction of overall GHG emissions compared to 1990: 40% until 2030 and 80-85% until 2050, (ii) emissions reduction from ETS sectors: 43% in 2030 and 90% in 2050 compared to 2005, (iii) non-ETS emissions reduction: 30% in 2030 compared to 2005 and (iv) energy efficiency: reduction of primary energy demand by 27% -30% in 2030 compared to 2007.

A clean planet for all scenarios

The *A Clean Planet for all* study presents a long-term vision on how "Europe can lead the way to climate neutrality by investing into realistic technological solutions, empowering citizens, and aligning action in key areas such as industrial policy, finance, or research – while ensuring social fairness for a just transition." (European Commission 2018b). Nine scenarios considering different areas of action, priorities and technological development are considered in this study. A baseline scenario is defined which, similar to the reference scenario in the *Clean Energy for all Europeans* study, does not meet the GHG emission reduction targets but is rather accompanied by a set of more ambitious decarbonization scenarios, distinguished by technological assumptions or emission targets.

3.2.2 Related EU research projects

There are multiple research projects funded by the EC that have engaged in extending the previously described work conducted by the EC. For example, the SET-Nav project ("Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation") defines pathways based on two major axes of uncertainty: cooperation vs. entrenchment and decentralisation vs. traditionally centralised ("path dependency"), see Crespo del Granado et al. (2020) and Figure 3.1. The SET-Nav pathways identify central drivers and role of these key uncertainties for a successful decarbonization of the energy system. This also entails discerning the consequences of the particular technological and political decisions that characterize each pathway. The four pathways are very diverse and therefore allow investigating a large number of drivers and uncertainties for the decarbonization of Europe. All the scenarios target 85% - 95% decarbonization by 2050. As another example, the REEEM project (REEEM Project 2019) studies the "role of technologies in an energy efficient economy [through] model based analysis policy measures and transformation pathways to a sustainable energy system." In this project, the pathway definition is based on a set of priorities listed by a number of stakeholders (decision makers, market actors and consumers) and focuses on six dimensions: political, economic, social, environmental, technological and global factors. These dimensions are studied in connection with the degree of cooperation between the EU member states, and form three pathways representing the most plausible development of the aforementioned dimensions. Also, the MEDEAS project - "Modeling the renewable energy transition in Europe" (Perissi, Falsini, and Bardi 2016) - defines three scenarios for describing possible future outcomes of the European energy transition. The first one is a business as usual (BAU) scenario, which is used to benchmark two alternative scenarios with stronger decarbonization policies. Similarly, the REFLEX project - "Analysis of the European Energy System" - analyses two main scenario strongly based on the PRIMES 2016 reference scenario (Capros et al. 2016) from the Clean Energy package of EC. The scenarios descriptions are based on modifications of recent projections, considering policy scenarios with ambitious decarbonization pathways (Herbst et al. 2016). Two scenarios are analysed: a moderate renewable scenario, which is comparable to a BAU scenario, and a high renewable scenario, which has higher decarbonization targets and CO_2 prices to reach a 2°C target.

3.2.3 Other European scenario studies

Besides the European Commission scenario assessment studies considered in the previous section, several other publications analyze the transition of the European energy system. As part of the scope in this review, studies with a deep decarbonization trajectory (i.e. reducing emissions by more than 80% by 2050) and with a multi-sector perspective (i.e., taking into account at least buildings, transport and the power system) are considered. It should, however, be noticed that these scenarios often do not provide quantitative information to support their claims about long-term decarbonization goals. Moreover, scenarios that lead to drastic emission reductions in the EU do not necessarily imply similar reductions for the rest of the world. Even though there are some similarities across studies, such as the assumed economic growth ranging from 1.4% to 1.7% per year, they differ in the scenario narratives, in the modelling approach and in the assumed policies.

In Table 3.1 some of the recent studies achieving around 90% GHG emission reduction by 2050 are summarized, placing these scenarios in accordance to the ambitions of the EGD. The first scenario reviewed has been published by Eurelectric in 2018 (Eurelectric 2018). The analysis shows the role of electrification when decarbonizing 80-95% of the EU economy in 2050, which is being achieved by switching from fossil-based generation to 94-96% carbon-free power, higher end-use efficiency due to electric mobility and electric heat pumps and the production of hydrogen and synthetic fuels. Another scenario has been developed by ClimAct and published by the European Climate Foundation (ECF) in 2018 with the objective of showing that a net-zero GHG emission target is technically and economically feasible by means of a distributed effort across sectors and levers (e.g. between technological change and demand-side interventions, see CLIMACT and ECF (2018)). Several studies have been published by the International Energy Agency (IEA) (International Energy Agency 2017, 2019), which focus on identifying the most economical way for society to reach the long-term climate goals and technology options and aimed at providing critical analysis on trends in energy demand and supply and on their implications for energy security, environmental protection and economic development. IRENA (2018) provides a study in Global Energy Transformation focused on long-term decarbonization and on the technical feasibility and socio-economic benefits of a global energy transition. Several studies have been carried out by the Joint Research Centre (JRC) of the European Commission. In particular, the Global Energy and Climate Outlook 2018 (Keramidas et al. 2018) provides a comprehensive analysis of the development of the energy markets under the simultaneous interactions of economic development, technological innovation and climate policies, while the Low Carbon Energy Observatory (Nijs et al. 2018) focuses on providing top-class data, analysis and intelligence on developments in low carbon energy supply technologies to support the definition of policy goals. A project initiated by nine key gas industry players named "Gas For Climate" has developed two scenarios to assess a cost-optimal way to fully decarbonize the EU energy system by 2050 and to explore the role of renewable and low-carbon gas used in conjunction with existing gas infrastructure (Terlouw et al. 2019). The scenarios are exogenously determined by renewable energy potentials, minimum and maximum technology shares in 2050 in end-use sectors, techno-economic parameters, energy efficiency and activity increase in final demand. A study, performed by F. C. Matthes et al. (2018) aims to show a pathway that "consistently combines short and medium-term objectives with long-term objectives". It meets a EU27 (plus UK) GHG emissions budget consistent with a 2°C limit on the global temperature increase.

A large emphasis on the reduction of GHG emissions from transport is placed by the study of Sven Teske (Teske 2019). The analysis looks towards reaching 100% renewable energy and near-zero emissions globally in order to meet the Paris Agreement goals, avoiding to rely on net-negative emissions. In 2018, the European wind industry's association WindEurope published a study with pathways for the decarbonization of EU energy system by electrification of industry, transport and by coupling power with heating and cooling (Pineda, Fraile, and Tardieu 2018). Besides the aforementioned scenario analyses, other studies have placed a particular focus on the EU electricity system. The report by Eurelectric (2011) introduces and discusses possible pathways to investigate the technical and economic feasibility of achieving an 80% overall GHG emission reduction by 2050, while maintaining or improving today's levels of electricity supply reliability, energy security, economic growth and overall prosperity. In the Eurelectric report by Eurelectric (2011), two major pathways are analysed: a reference case and the 'Power Choices' case. The scenarios base the emission reduction on the development of technology both on the supply and the demand side. The study finds that the major emission reductions happen between 2025 and 2040, and it is dependent on technological development, carbon policy and a paradigm shift in the energy demand sector fostering smart operation. In Jägemann et al. (2013) the focus is on different cost developments for power supply technology, which lead to different technological pathways. The study claims that the decarbonization of Europe's power sector is achieved at minimal costs under a stand-alone CO_2 reduction target, which ensures competition between all low-carbon technologies. These cost rise significantly if investments in new nuclear and CCTS power plants are politically restricted. In Fraunhofer Institute for Systems and Innovation Research ISI (2014) there are three scenarios defined on the basis of three main aspects: development of low-carbon supply technologies, different demand projections and public acceptance. The results of the study indicate that more efficient electricity consumption is an important element of moderating the cost of decarbonization and that large shares of variable RES calls for significant transmission expansion. Also, in Burandt, Löffler, and Hainsch (2018) the focus turns into the realization of policies but with a more complete perspective on different energy carriers and multi-sector coupling effects.

Other approaches both define and assess scenarios on a global perspective. As a mention CenSES 2019 focuses on shared socio-economic pathways (SSP) to analyse both global and European power sector context. The study derives eight scenarios until 2050 and couple the emission constraints based on Representative Concentration Pathways to a European power system model. In Child et al. 2019a, the authors study the Pathways to assess the feasibility of a 100% RES-based electricity generation mix by 2050 in 20 European countries and aggregated regions. According to the results of the paper, a centralized European expansion of the power grid would allow the power system to transition towards a fully renewable structure which results not only technically feasible, but also economically viable due to the reduction of the related levelized cost of electricity throughout Europe.

3.2.4 Scenario definition: at the crossroads of policy-technology-society developments

Achieving net-zero GHG emissions by 2050 sparked the development of several studies to assess the technical feasibility of a fully decarbonized energy systems and its socio-economic implications. Based on this review, it is noticeable that when defining storylines most studies tend to simply introduce variations on technology development and its rate of deployment. For example, assumptions on the evolution of energy efficiency rates or the learning curves of some technologies. As part of the scenario definition this is combined with cost projections and other technology specific assumptions. Some scenario definitions might introduce some geopolitical factors and policy assumptions (mostly some form of CO_2 cap) to complement the drivers in technological development. While other scenario definition, put some emphasis on how the policy outlook might shape the technological progression and choices (see policy and technology columns in Tables 3.1 and 3.2.4).

Other energy transition scenarios, have engaged into a more creative process on defining their storylines by assuming that these are shaped by the impact of two set of future drivers or uncertainty developments. For example, Figure 3.1 illustrates three pathways definition shaped by a 2x2 typology where the dimensions constructs the definition of four pathways (shared quadrants). In SET-Nav, with the degree of cooperation versus the level

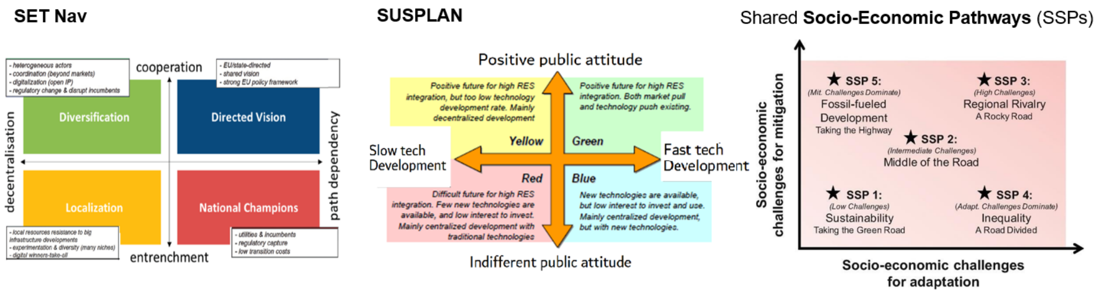


Figure 3.1: Examples of widely-used 2x2 scenario typology to combine two main dimensions of uncertainty into four storylines spanning a wide possibility space.

of decentralization, the storylines assume that policy directions will be shaped by cooperation while technology development might have different market and deployment prospects. In SUSPLAN, the intersection of societal attitudes and technology uptake provides different notions on how policy in storylines should be defined. Lastly, the well-known shared socio-economic pathways create storylines on the dimensions of mitigation challenges versus adaptation challenges. This results in five storylines that prescribe policy and technology assumptions as a result of their positioning in the quadrant.

All in all, the different reviewed forms of storylines, scenarios and pathways definitions tend to one way or another assume an interplay between policy exertion, technological development, and societal attitudes. The latter is not much explored in the formation of storylines assumptions (see societal columns in Tables 3.1 and 3.2.4). In this paper, we propose an original and creative way to encompass these three drivers (or uncertainties) to form a set of storylines. That is, the European energy transition will be at the crossroads of policy-technology-society developments by understanding the trade-offs and synergies among them.

Table 3.1: An overview of existing decarbonization scenarios for EU (continues...)

European based study or project	**Scenario ambition (ref. 1990) & year**	**Technology innovation assumptions**	**Policy assumptions**	**Societal / behavioural assumptions**
Eurelectric (Eurelectric 2018)	Over 90% GHG reduction towards 2050	Mature technologies experience steep cost reductions towards 2030. Breakthrough technologies at an early stage of innovation reaching broad commercial scale before 2040	The regulation drivers expect major shifts in policies, tariffs and taxes, driving earlier shift and removing current barriers to electrification, on top of the emission reduction targets	Clean technologies to progressively become mainstream and increasingly competitive for consumers. High competitiveness of electricity against other energy carriers
CLIMACT and ECF 2018	near 100% GHG reduction towards 2050	Energy efficiency, H_2, CCTS are heavily exploited (e.g. 96% of the EU building stock renovated by 2050)	No new investments in Nuclear	Recycling, wider product lifetime, circular economy, transport transformed into a service
ETP B2DS - IEA, International Energy Agency 2017	92% GHG reduction towards 2050	Technologies available and in the innovation pipeline that can make their commercial scale deployment by 2060.	Nationally Determined Contributions	Not considered
IRENA 2018	84% GHG reduction by 2050 (2 degrees target reached in 2100)	CCTS is deployed only in certain industry sub-segments	Emission levels compatible with the global temperature increase trajectories	Decarbonization of buildings and industry through increased use of electricity
GECO - JRC (Keramidas et al. 2018)	96% GHG reduction towards 2050	Not defined	CO_2 emission constraints	New mobility patterns such as car sharing
LCEO - JRC (Nijs et al. 2018)	100% GHG reduction towards 2050	CCTS limited to 300 $MtCO_2$ annually, nuclear expansion allowed in countries with no restrictions. Large amount of RES, H_2 and e-fuels	CO_2 emission constraints	Not considered

Table 3.1: An overview of existing decarbonization scenarios for EU (continuation)

European based study or project	**Scenario ambition (ref. 1990) & year**	**Technology innovation assumptions**	**Policy assumptions**	**Societal / behavioural assumptions**
Gas for Climate - Navigant consulting Inc. (Terlouw et al. 2019)	100% GHG reduction towards 2050	Renewable Low Carbon gas to be used in the existing gas infrastructure. Electricity produced with RES and biomass or RES and H_2	Not defined	Electrification of buildings.
F. C. Matthes et al. 2018	99% GHG reduction towards 2050	Limits to use of CCTS only in industrial processes, nuclear phaseout and biomass. Increase in energy efficiency.	Carbon budget constraints. e-fuels are from extra-EU imports	No major behavioural changes
Achieving the Paris Climate Agreement Goals -(Teske 2019)	100% GHG reduction towards 2050	Sequestration of GHG by land and forests. no CCTS. Electric based transport and H_2	Regional Constraints, No nuclear power, no unsustainable biomasses	Shift within transport consumption to more sustainable alternatives. Decrease in car based private transportation
Pineda, Fraile, and Tardieu 2018	90% GHG reduction towards 2050	Coupling power with heating and cooling. H_2. Electrification and Energy Efficiency.	Carbon pricing beyond those covered by EU ETS (90€/tCO_2 in 2050). Decommissioning of coal-based power plants	Not considered
Eurelectric, Eurelectric 2011	-40%/-75% GHG red. by 2030/2050 (ref.1990)	Increased efficiency and CCTS from 2025, demand response	CO_2 cap	Public acceptance of land use for RES, electrification of transport
Jägemann et al. 2013	–80 – 95% GHG red. by 2050 (ref.1990)	Increased efficiency and CCTS from 2030	CO_2 cap, RES targets, technology restrictions (CCTS and nuclear)	Not considered

Table 3.1: An overview of existing decarbonization scenarios for EU (continuation)

European based study or project	**Scenario ambition (ref. 1990) & year**	**Technology innovation assumptions**	**Policy assumptions**	**Societal / behavioural assumptions**
Fraunhofer Institute for Systems and Innovation Research ISI 2014	-95% GHG red. by 2050 (ref.1990)	Increased efficiency and CCTS	National RES targets and required national supply (restricted import) of 85%, CO_2cap	Public acceptance of land use for RES, demand growth, electrification of transport
FME CenSES (CenSES 2019)	RCP 2.6/3.7/4.5 by 2050	Increased efficiency and CCTS	CO_2 cap	Not considered
GENeSYS-MOD (Burandt, Löffler, and Hainsch 2018)	<2°C by 2050 (carbon budget IPCC AR5)	Increased efficiency and CCTS	CO_2 cap	Not considered
Child et al. 2019a	100% RES in power sector by 2050	Decreased costs for RES and storage, prosumer growth	CO_2 cap	Public acceptance of transmission

3.3 The openENTRANCE scenario definition approach and quantification

3.3.1 Defining scenarios for low-carbon futures: A 3D framework concept

Narrative descriptions of possible developments, structures and characteristics of future energy systems based on different storylines are suitable for systematically mapping all uncertainties ahead. In general, there is no preferred or most likely storyline. Existing literature developing climate and energy system related storylines so far has relied on methodologies enabling a differentiation of the individual narratives based on (i) the dimension of analyses topology determining the number of individual storylines, and (ii) nomination of key drivers and feature of the individual storylines highlighting the uniqueness of each one. In terms of topology, a two-dimensional approach emphasizes two key uncertainties describing possible future energy worlds, where a positive and negative expression of these two uncertainties results in four different storylines (3.1). In terms of key drivers and features, storytelling mainly emphasizes the questions (i) why a certain development is expected to happen and (ii) what happens.

The two main innovations of the openENTRANCE storyline approach are as follows: Firstly, the storyline topology is extended into a three-dimensional space in which each of the three dimensions determines the salience of a particular uncertain development, namely technological novelty, policy exertion, and societal attitude. The further one moves in this three-dimensional space from the origin of a coordinate system, the stronger is the expression of the respective determinant and thus the disruption from the existing energy system. In openENTRANCE, the combination of two exposed determinants, with the third being less important, results in three distinct storylines that highlight each possible pair of combinations between technology, policy and society. The fourth storyline, near the origin of the coordinate system, contains ”a bit of each” of the three uncertain developments and is thus the least distinct (see Figure 3.2). Secondly, openENTRANCE storytelling directly addresses the current global climate debate and attempts to better connect both disciplines, energy and climate modelling. More precisely, the expectation of climate neutrality in 2050 (i.e. a 100 per cent reduction in GHG emissions compared to 1990) would limit the global temperature increase to 1.5°C - 2°C and avoid some of the worst climate impacts. In this context, one of the most important linking parameters between energy and climate modelling in openENTRANCE is the so-called remaining CO_2-budget, notably the European fraction, which in turn is directly linked to global temperature rise. This allows us to link the different openENTRANCE storylines directly to a certain limit value for the global temperature increase. The three distinct openENTRANCE storylines at the exposed corners of the cube in Figure 3.3 (*Societal Commitment*, *Directed Transition*, *Techno-Friendly*) correspond to the European contribution to the global 1.5°C target. The less exposed storyline close to the origin of the coordinate system (*Gradual Development*) refers to the less ambitious 2°C target.

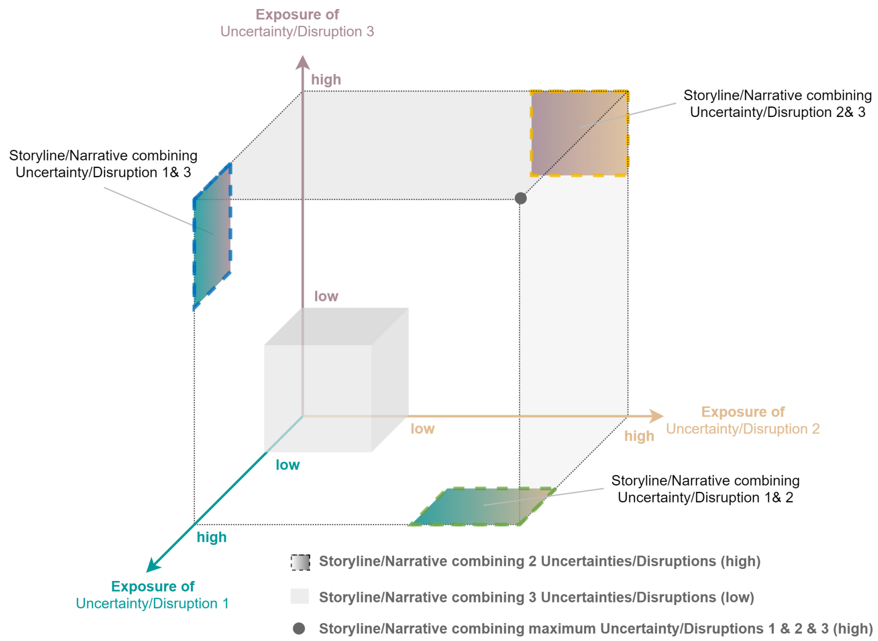


Figure 3.2: 3D concept for a scenario generation process. The axes represent the salience of a particular uncertain development.

3.3.2 Pathway description and model setup

3.3.2.1 Societal Commitment

High societal engagement and awareness of the importance to become a low-carbon society characterizes this storyline. Individuals, communities and the overall public attitude support strong policy measures to accelerate the energy transition. Both grassroots (bottom-up) and top-down government led approaches meet to drive the strong uptake of behavioural changes in energy usage and energy choices from European citizens. Hence, "green" government initiatives drive and direct ambitious measures in decarbonizing the energy and transport sectors. However, the pathway assumes that no technological breakthroughs occur and there is a lack of major achievements in technology development. It

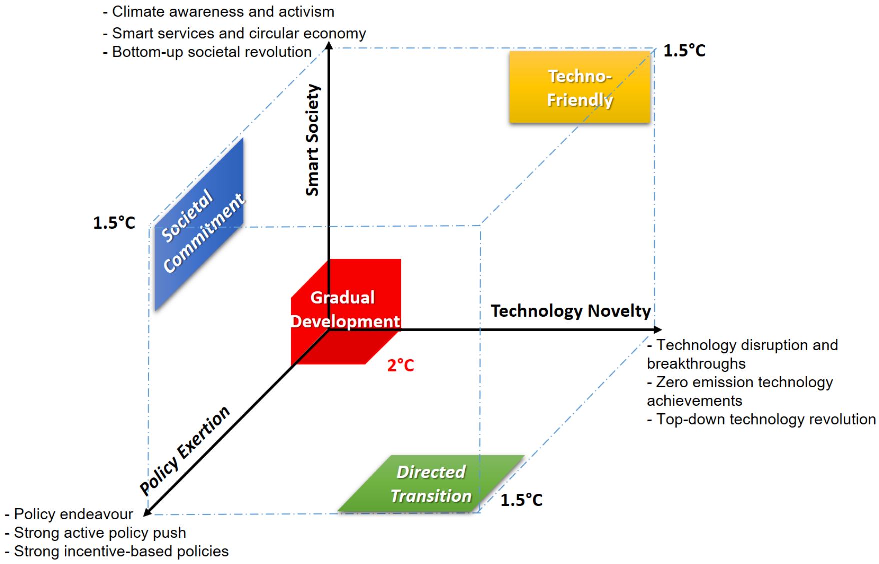


Figure 3.3: Pathways storylines typology = policy exertion x technological novelty x smart society. The three dimensions set the scene on three disruptors or uncertainties which together creates four storylines (coloured squares).

relies on a policy mix that has wide-support from the public. The key driver of this storyline is that society as a whole embraces cleaner and smarter life styles with the public sector working with and supporting grassroots initiatives.

3.3.2.2 Directed Transition

Carbon-mitigating energy technologies emerge and require strong policy incentives for their uptake and development. The storyline assumes that the effect of grassroots and citizen-led initiatives will be minimal but that strong policy incentives can drive the required engagement of citizens to reach climate targets. This storyline is driven by a strong centralized vision on the part of policymakers and direct partnerships with industry and technology developers who respond to incentives provided by the public sector and provide broad advances in low-carbon energy-related technologies.

3.3.2.3 Techno-Friendly

A positive societal attitude towards lowering GHG emissions translates into welcoming the deployment of new technologies and changes in behavioural energy choices and grassroots movements in energy. Little resistance to adopting new technologies and openness to large-scale infrastructure projects characterize the social developments of this storyline. Centralized decision-making and policy steering are difficult to reach and hence limited in this storyline, and thus the drive of this storyline comes from grassroots initiatives and industry taking action to deliver novel technology. The narrative centres on technological novelties complemented with sustained technology uptake by citizens such that demand for new carbon-mitigating energy technologies drives market-based development of these technologies on the part of industry actors. Partly new business models and social innovations pick up the slack from the lack of policy action.

3.3.2.4 Gradual Development

This storyline envisions that the climate target (2°C) is reached through an equal part of societal, industry/technology and policy action. Knowing that a continuation of current public policies and developments are expected to not be sufficient, significantly higher efforts are needed than the current level of commitment of several of the actors. Thus, this storyline entails ingredients of ‘a little of each’ of the previously described openENTRANCE storylines and therefore represents an already ambitious reference scenario in openENTRANCE.

3.3.2.5 Quantification process of the pathways with GENeSYS-MOD

The quantification of the storylines described in the previous sections is carried out with the help of GENeSYS-MOD which is based on the OSeMOSYS (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Howells et al. 2011a).[2] GENeSYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission reduction targets, integration of RES and sector-coupling. The model minimizes the objective function which comprises total system costs (encompassing all costs occurring over the modeled time period) and was used in multiple case studies analyzing regional, continental or the global energy system (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Löffler et al. 2019; Burandt, Löffler, and Hainsch 2018; Burandt et al. 2019; Bartholdsen et al. 2019; Hainsch et al. 2021).[3]

Energy and energy service demands for the sectors electricity, buildings, industry and transportation are given exogenously for each time-step, with the model computing the optimal flows of energy and the resulting needs for capacity additions and storages. To achieve

[2] Additional information about the different storylines and their implementation in GENeSYS-MOD can be found in the Appendix A.

[3] For more information about GENeSYS-MOD including a documentation, quick-start guide, and sample dataset, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public

these results, the model can choose from a plethora of technologies spanning across the mentioned sectors, with sector-coupling and storage options being key functionalities. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g., to limit the usable potential of RES), RES feed-in (e.g., to ensure grid stability) or emission budgets (implemented either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and realistic results.

The translation of the openENTRANCE storylines into GENeSYS-MOD-input is achieved through a number of parameters and model functionalities. Features which are accounted for in all pathways such as decreasing fossil fuel prices, technology learning curves or energy demand changes are straightforward to implement, since suitable parameters already exist in the model. Other aspects are either pathway dependent,[4] require the implementation of new features such as the possibility for limited amounts of load shift during a day or are achieved through workarounds (e.g., the implementation of car-sharing is achieved through increasing annual mileage of cars, resulting in less vehicles needed to accommodate the demand).[5] All results are available to the public via an open platform developed and hosted by the International Institute for Applied Systems Analysis (IIASA).[6]

3.3.3 Results of the openENTRANCE pathways

All four pathways calculated in the openENTRANCE project show similar developments when it comes to the main indicators of the energy system. In order to decarbonize currently fossil-fuel dominated sectors (i.e., heating and industry), electricity based technologies, powered by 100% renewable electricity, are the option of choice. As a direct consequence, power capacities and production experience a significant increase until 2050, since the additional demand from all sectors outnumbers the efficiency gains of electrical appliances. In contrast, the overall demand for primary energy decreases substantially due to generally higher efficiency of these electricity based technologies (e.g., BEVs, heat-pumps, etc.). The most notable effect on primary energy consumption can be observed in the *Societal Commitment* pathway and its significantly reduced final energy demand, while efficiency gains in the *Techno-Friendly* scenario have a higher impact on the electricity generation.

Societal Commitment, *Directed Transition*, and *Techno-Friendly* (the 1.5°C pathways) all show a (nearly) full decarbonization by 2040, while the *Gradual Development* pathway

[4]Examples are, among others: the consideration of overhead-trucks (*Techno-Friendly*), EU-wide phase-out of nuclear power plants (*Societal Commitment*) or setting annual emission reduction targets (*Directed Transition*)

[5]A full description of the implementation of the storylines can be found at https://openentrance.eu/2020/05/05/quantitative-scenarios-2/

[6]The open platform can be accessed via: https://data.ece.iiasa.ac.at/openentrance

reaches that milestone ten years later in 2050. However, as illustrated in Figure 3.4, the delayed achievement of full decarbonization comes at the costs of higher primary energy and electricity demand for *Gradual Development*.

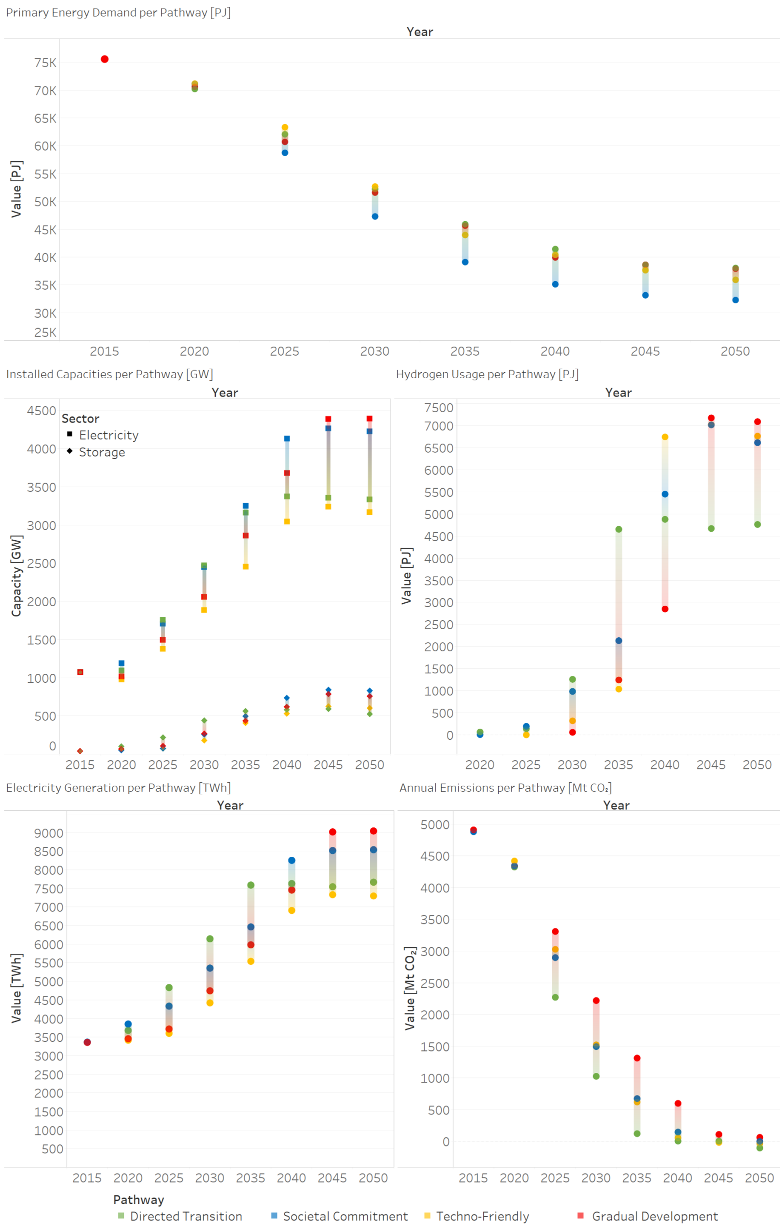


Figure 3.4: Comparison of key indicators for all pathways.[7]

[7]For further information on the openENTRANCE pathways, as well as more detailed results, the reader is referred to Auer et al. (2020).

Another difference in pathway results lies in the degree of availability of CCTS technology. If the costs of CCTS are low enough to compete with other means of decarbonizing the energy system (i.e., in the *Techno-Friendly* and *Directed Transition* pathway), the primary area of application is the high-temperature industry sector and, to a lesser degree, also the power sector. Nuclear power, being another non-fossil but also non-renewable source of energy, is more sensitive to the characteristics of the respective pathways: limited societal acceptance of nuclear and fossil generated power (*Societal Commitment*) leads to a phase-out by 2040, while a continuation of current projections (*Directed Transition* and *Gradual Development*) results in remaining capacities in France and Eastern Europe, which in some cases are even expanded. Nevertheless, the majority of electricity originates from wind (on- and offshore) as well as photovoltaics across all four pathways.

Another interesting difference in pathway results can be observed when analyzing the speed and time frames of technology deployment: *Directed Transition*, with the decarbonization mainly being driven by direct policy instruments, shows a sharp increase in capacity expansion until 2040, whereas afterwards the numbers stagnate due to less technological and societal development. *Gradual Development*, on the other hand, experiences the exact opposite development since the reduced action in the first years has to be compensated in the second half of the modelling period by high amounts of capacity expansions in the power sector. Similarly, this effect also carries over to hydrogen production and consumption.

Overall, these results indicate that a strong policy enforcement of climate goals in the short term does drastically affect the speed of the energy transition. Especially when considering the accumulated emissions, *Directed Transition* with its lower short-term emissions leads the way. While the other pathways also reach their designated climate targets, the decarbonization process moves further into the future, since break-through technologies and societal behavior require significant time to become effective. This underlines once more the importance of policy measures to ease the future energy transition.

Table 3.2: Overview of key results of the four openENTRANCE pathways.

	Year	Directed Transition	Gradual Development	Societal Commitment	Techno-Friendly
Primary Energy [PJ]	2030	52,295	51,575	47,289	52,670
	2050	38,516	38,245	32,417	35,675
Power Capacities [GW]	2030	2,469	2,059	2,448	1,884
	2050	3,331	4,394	4,222	3,164
Electrification Volume [TWh]	2030	6,028	4,722	5,342	4,374
	2050	7,373	8,453	7,714	7,026
Hydrogen Volume [PJ]	2030	1,260	60	985	321
	2050	4,761	7,086	6,611	6,760

3.4 Comparison of openENTRANCE pathways with similar pan-European pathways

The results of the four different openENTRANCE pathways illustrate how a coherent set of input assumptions can lead to insightful results in the field of energy system modelling. In the next step, these results are compared with other prominent studies which focus on high degrees of decarbonization of the European energy system by using similar tools and methodologies as in the openENTRANCE project. Tsiropuolus et al. (2020) identified 26 publications between 2017 and mid-2019 on energy scenarios, mainly stemming from governmental organisations and the private sector. Out of the 67 scenarios which where analysed in these 26 publications, eight studies reach (almost) full decarbonization of the European energy system by 2050 while at the same time achieving significant GHG emissions reduction in 2030 of at least 55% compared to 1990. These publications are of great value, since they not only allow a verification of the results of the openENTRANCE pathways but also for a more in-depth analysis on common findings, especially with regard to policy recommendations and no-regret options in the energy transition.

Therefore, two other studies will be analyzed and compared to the openENTRANCE pathways. The criteria for selecting said studies where, on the one hand, the choice of methodology, which had to be similar or at least comparable to the approach used for the openENTRANCE pathways, and, on the other hand, ambitious decarbonization targets for 2030 and 2050. Two other studies perfectly matched these criteria, one being the *A clean planet for all* study by the European Commission (2018b) including two suitable scenarios (*1.5Life* and *1.5Tech*) and the other one being *Deployment Scenarios for Low Carbon Energy Technologies* by the JRC (Nijs et al. 2018) with the *near ZeroCarbon* scenario.[8] The comparison is focused on the final energy consumption per fuel and per sector, the electrification rate within the sectors as well as the required power capacities. Since the regional coverage differs between the studies, with for example Turkey being considered in openENTRANCE, the results for the EU27 countries plus Norway, Switzerland and the UK are being compared to ensure proper comparability of the different studies.

Comparing the final energy consumption (see Figure 3.5), all pathways show a total consumption within the same range of 600 to 1000 mtoe. However, the openENTRANCE pathways show generally higher final energy consumption in 2050 compared to the other studies. This is most likely due to a difference in the implementation of the industry sector, as well as Norway and Switzerland being included in the openENTRANCE pathways. Also, the share of ambient heat is noticeably higher in the openENTRANCE pathways, due to higher penetration of heat pumps in the buildings sector, and general ”heat” not being

[8] For a brief summary of the scope of these projects, the reader is referred to the Appendix.

listed as its own entity. The shares of hydrogen, biomass and electricity are very consistent across all pathways, with the largest discrepancy shown in the usage of fossil fuels. In the *Societal Commitment* pathway of the openENTRANCE project, societal attitude towards nuclear and CCTS technology leads to 0% usage of fossil fuels in 2050, while the techno-economical availability of the latter enables the use of limited amounts of fossil fuels in the *Techno-Friendly* pathway.

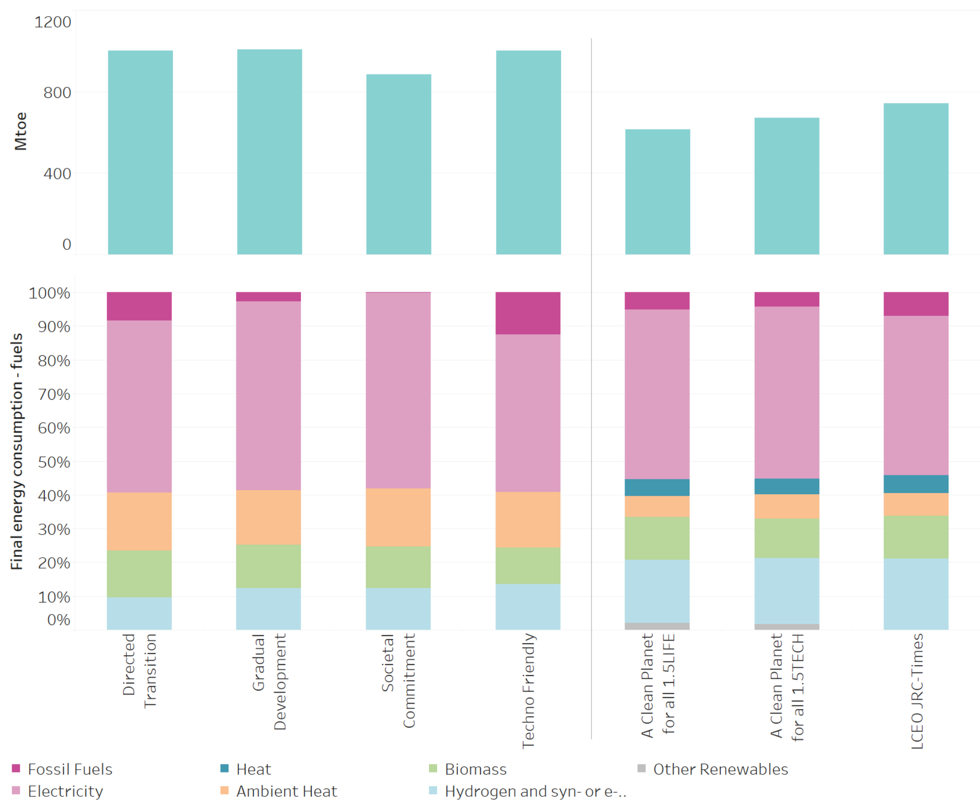


Figure 3.5: Comparison of final energy consumption per fuel and total energy demand in 2050 at EU27 level (including Norway, Switzerland and the UK) according to assessed pathways and scenarios.

Looking at the sector-wise distribution of final energy consumption in Figure 3.6, the share of the buildings sector is experiencing similar shares across all analyzed pathways. The biggest difference is in the industry and transport sectors, where some openENTRANCE pathways differ substantially from the other studies. This can be explained by the pathway assumptions and technology options of the model. In the *Techno Friendly* pathway, for example, trolley trucks powered by overhead power lines are enabled as a technology option, leading to a drastically reduced final energy demand in freight transportation due to the higher energy efficiency. The industrial sector, on the other hand, experiences a higher share due to a higher usage of hydrogen, which, compared to it's electric counterparts, requires more energy due to conversion losses.

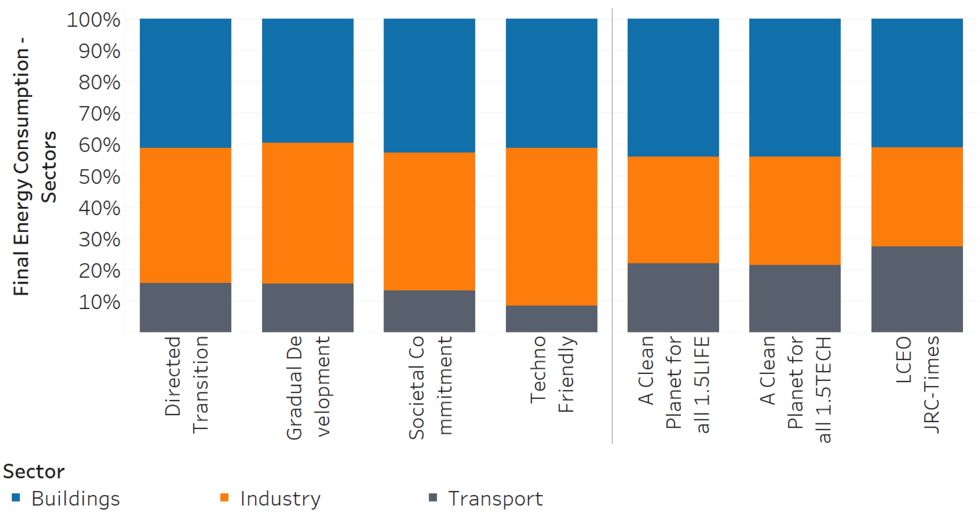


Figure 3.6: Comparison of final energy consumption per sector in 2050 at EU27 level (including Norway, Switzerland and the UK) according to assessed pathways and scenarios.

The electrification rates (shown in Figure 3.7) also confirm that development: *Techno Friendly* has the lowest electrification rate in industry across all pathways, but by far the highest in transport. The electrification rate for buildings is rather consistent across all seven pathways, staying within 58-72%. The same goes for transport, which sees an electrification rate of roughly 32-39%, with the aforementioned exception of the *Techno Friendly* pathway. The industry sector is the only one seeing a meaningful spread, with the openENTRANCE pathways experiencing a strictly higher electrification rate than the other studies. This might, again, be due to differences in the details of the representation of the industry sector (e.g. which areas are covered exactly and at what level of detail). The highest electrification rate in industry is seen in the *Societal Commitment* pathway with a share of close to 80% electrification. The reasons for that observation lie in the unavailability of CCTS technology, limited technological development of hydrogen based technologies as well as the highest carbon price across all pathways.

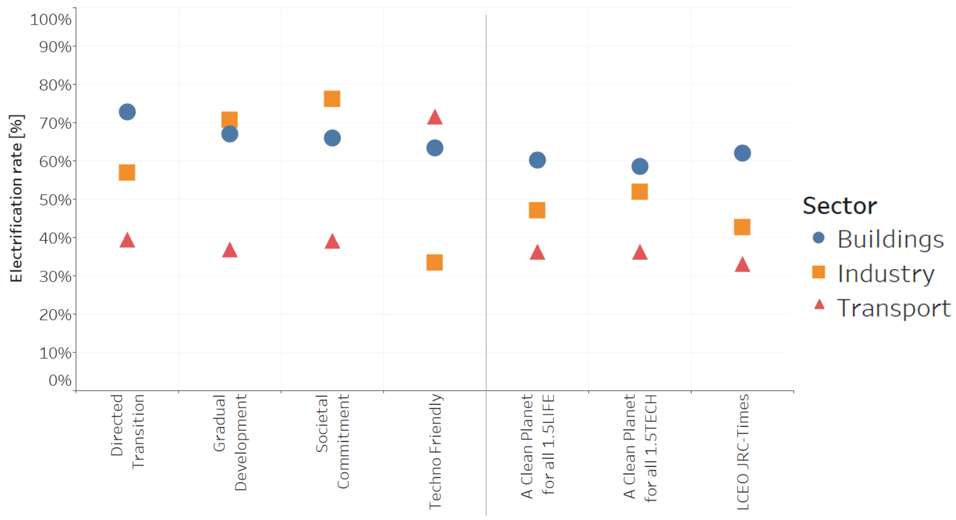


Figure 3.7: Electrification rate of the different sectors in 2050 at EU27 level (including Norway, Switzerland and the UK) according to assessed pathways and scenarios.

Finally, the installed capacities of electricity generating technologies are compared to provide a better understanding on how these high degrees of electrification in the sectors buildings, industry and transportation are facilitated. Figure 3.8 illustrates the overall installed capacities in 2030 (left) and 2050 (right) in GW across the different assessed pathways. A general observation for the 2030 values is that the openENTRANCE pathways overall show higher amounts of installed capacity, mainly being onshore wind and solar PV, which can be explained by the higher decarbonization values in 2030 which are achieved by these pathways. The amount of fossil capacities is very similar across all scenarios, with the *LCEO* pathway being the exception showing slightly higher remaining capacities. In 2050, the significant difference between the *LCEO* pathway and all others is striking. A possible explanation could be the more prominent role of hydrogen in this scenario, which is being used to a large degree in the transportation and industry sector but even goes as far as being used in the power sector. Another interesting observation is that, while in the openENTRANCE pathways the *Techno-Friendly* scenario results in the least amount of required capacities (due to higher technology efficiencies, especially in other sectors which in turn result in less power demand), the *A Clean Planet for All* study shows the opposite effect, with the society and lifestyle driven pathway being less demanding on electricity. This can originate from substantially reduced demands in the *1.5LIFE* pathway, while at the same time the Societal Commitment scenario in openENTRANCE does not show the utilization of nuclear or fossil fuels, which consequently leads to higher renewable capacities being required.

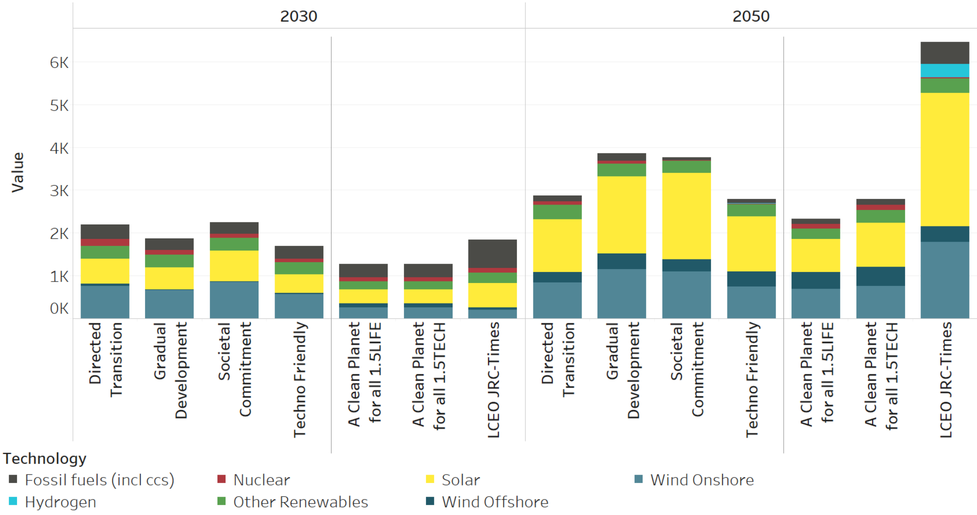


Figure 3.8: Comparison of cumulative installed capacities of power generation technologies by 2050 at EU27 level (including Norway, Switzerland and the UK) according to assessed pathways and scenarios.

3.5 Discussion and policy recommendation

The comparison in the previous chapter of the different scenarios shows a large amount of similarities between the different pathways. Yet, at the same time, differences exist with the reason for said discrepancies not being necessarily apparent at first glance. In general, underlying assumptions, temporal/spatial/sectoral scope, and structure of the model are all factors which have to be considered when analyzing scenario results - especially when comparing outcomes from different models. This raises the challenge for policy makers who, therefore, rely on modelers and researchers to prepare and present model results in a comprehensive way. To address this need, the following section provides an overview of of key findings and recommendations which are found in the compared scenarios, while at the same time highlighting their consideration in the EGD.

As mentioned in the introduction, the EGD aims at a wide rang of fields with regard to climate change mitigation and sustainability. Table 3.3 shows a number of areas the EGD is targeting with different actions plans, defined by the European Commission (2019b), and some of the action plans' key components. Coming back to the three-dimensional space of technology, policy, and society, the table also highlights recommendations and key findings found across the results of the different scenarios analyzed in Section 3.4.

Table 3.3: Key areas of action of the European Green deal and related recommendations and key findings found across the compared studies, distinguished by the dimensions technology, policy and society. If the recommendations and findings overlap for two or more dimensions, the cells are merged into a single cell for both.

	Coverage in EU Green Deal	Recommendations and key findings		
		Technology	Policy	Society
Electricity	A power sector must be developed that is based largely on renewable sources, complemented by the rapid phasing out of coal and decarbonising gas; Increasing offshore wind production will be essential, building on regional cooperation between Member states	- Renewables are the cornerstone of emission reductions in the power sector - Power demand is projected to increase and large-scale investments are needed to cover future electrification demand - Storages are key to provide flexibility for the power system - Caution needs to be placed regarding investments in gas infrastructure, as any investments into fossil fuels (including natural gas) risk being stranded		- Large-scale introduction of renewables provides opportunities to convert existing jobs in the fossil sector and create new high-qualification job opportunities - Public acceptance of renewables is an important factor, considering the amount of renewables required
Industry	The Commission will support clean steel breakthrough technologies leading to a zero-carbon steel making process by 2030	- CCTS can reduce emissions in difficult to decarbonize industry branches - Carbon-free steel, cement, and aluminium production can be likely be fueled by hydrogen	- Develop strategies for all difficult to decarbonize industry branches, such as chemical, cement, aluminum industries - Early and clear regulation required for industry to have security about future developments	- Promote consumption of sustainable products - Support R&D endeviors of firms to transition to low-carbon production means
Buildings	'Renovation wave' initiative for the building sector; annual renovation rate of the building stock varies from 0.4 to 1.2% in the Member States. This rate will need at least to double	- Heat pumps are essential to minimze carbon footprint of buildings, together with retrofitting and renovation of existing buildings	- Building renovation rate is lower than required and often not even achieved in reality - Binding minimal rates for building renovation should be considered - Private home-owners would need to be supported to incentivize the switch to heatpumps and implement energy efficiency measures	
Transport	90% reduction in transport emissions is needed by 2050; 75% of inland freight carried today by road should shift onto rail and inland waterways; ramp-up the production and deployment of sustainable alternative transport fuels; By 2025, about 1 million public recharging and refuelling stations will be needed for the 13 million zero- and low-emission vehicles expected on European roads; to ensure a clear pathway from 2025 onwards towards zero-emission mobility; will consider applying European emissions trading to road transport	- At least half or more of passenger vehicles need to be electric by 2030 - Investments and subsidies for BEV charging stations are required to provide the neccessary infrastructure for low-carbon road transport - Hydrogen can provide ancillary services for road-based transport (especially heavy-duty transport) - Overhead-trolley trucks can provide large shares of freight transportation services, albeit having high infrastructure investment costs - Promotion of rail transportation for both freight and passenger transport necessary to reach desired effects		- Car-sharing and -pooling have significant effect on transport emissions and vehicle ownership - Difficult to decarbonize freight transport could be supported by changed consumption behaviour
Climate	Proposal on a European 'Climate Law' enshrining the 2050 climate neutrality objective; no net emissions of greenhouse gases in 2050; to increase the EU's greenhouse gas emission reductions target for 2030 to at least 50% and towards 55% compared with 1990 levels in a responsible way	- Current climate targets not sufficient to be in line with 1.5 °C target - Increasing the 2030 climate target is necessary to not put too much pressure on the years 2030-2050		
Carbon Price	The Commission will propose a carbon border adjustment mechanism, for selected sectors, to reduce the risk of carbon leakage; possibility of including emissions from buildings in European emissions trading	- Carbon price suited for a majority of decarbonization, but very high numbers required for 100% - Energy sector better suited for a carbon price than e.g. the buildings sector, where infrastructure investments play a larger role		
Sufficiency and Circ. Econ.	Strategy for sustainable and smart mobility; Circular Economy Action Plan; Legislation on batteries in support of the Strategic Action Plan on Batteries and the circular economy	- Battery recycling and second life of e.g. batteries from Battery-electric-vehicles are important for resource optimization	- Develop strategies tackling sufficiency and behavioural changes in society	- Demand reduction shows overall high effect on projected costs, emissions and electrification rates

Starting the analysis with the electricity sector, all studies point to a rapid phase-in of RES while at the same time a phase-out of fossil technologies is required. This is also reflected in the action plans defined in the EGD, but the also mentioned decarbonization of natural gas has to be treated with caution, since infrastructure investments into natural gas can quickly become stranded, if the technologies for producing carbon-free gas do not experience a significant reduction in costs. With high amounts of renewables and the resulting shift in the overall system, the job landscape will change with a large number of new jobs being created. Handling the implied change in requirements for employees, as well as the promotion of RES to raise the public acceptance will be one of the key challenges for a successful energy transition.

The industry sector faces the challenge of decarbonizing difficult to electrify industry branches (e.g., the steel or cement industry). Hydrogen seems to be one of the enablers of such a transformation, with CCTS only showing potential if the costs decrease substantially compared to todays development. Moreover, with capture rates of 90%-95% (Garcia Freites and Jones 2020), CCTS is not suitable for a complete decarbonization of the respective processes. Apart from the required strategies to defossilize all industry branches, out of which the EGD currently only targets the steel production, early and clear regulations are necessary to provide sufficient planning security for firms. Additionally, the use of hydrogen (H_2) needs to be analysed in a holistic approach, since currently it is viewed as the main transition enabler in multiple sectors, yet its potential is limited, especially if imports of H_2 are not an option. Another aspect which has to be emphasized is the promotion of sustainable consumption as well as sufficiency. Efficient recycling of materials (e.g. in the steel industry) or less demand for industrial products in general could provide a substantial part in decarbonizing the industrial sector and strategies need to be developed to support this shift.

In the buildings sector, in contrast, political targets are set but mostly fail in being achieved in reality. The renovation rate of houses and their insulation is one of the best ways of reducing building energy consumption and the EC plans to increase the target with a ”Renovation Wave” initiative. Supplemented by the installation of efficient and clean heat sources, like heatpumps or other electricity-based solutions (and to a limited degree also hydrogen fueled), energy consumption and emissions in the buildings sector can be reduced significantly. However, incentives and financial support mechanisms should be put in place for private house owners, since renovations and change of heating infrastructure come hand in hand with large amounts of expenses which is another reason why the current transition progresses slower than required (Verhagen, Voet, and Sprecher 2020). This has to be accompanied by stopping all financial incentives to install non-renewable heating systems, as their extremely slow replacement rates would slow down the required transition.

The last of the four main energy sectors, the transportation sector, being the sector with an increase in total emissions since 1990 instead of a decrease (European Commission 2020a), requires a fundamental overhaul which is also acknowledged in the EGD. Road transport (passenger and freight) has to be electrified (including the use of hydrogen generated with RES), the use of public transport and rail transportation in general needs to be amplified, and investments into charging infrastructure for BEVs are required to rapidly decrease the emissions in the transportation sector. However, transportation is largely influenced by the behaviour of society (e.g., travel behaviour, consumption behaviour and related freight transportation, but also car-sharing or -pooling concepts) and is likely to require a societal change as well to support the technological transition. Enabling and promoting this integrated transformation will be the key determinant to the successful decarbonization of the transportation sector, with the societal part being less explored in the current version of the EGD. This ties into the aspects of sufficiency and circular economy, as demand reductions prove to be one of the key measures to reduce overall emissions (Löffler et al, same issue). Another example already envisioned by the EGD is the sustainable production of batteries and possible reuse of batteries from BEVs in the power sector - the so-called second life.

Overall, the EGD put in place many necessary plans in order to achieve the decarbonization of the European energy system, as illustrated by the scenario calculations of the openENTRANCE project but also many other institutions and projects. Yet, the speed at which the required changes are implemented will have to increase for a successful transformation, a fact also illustrated by the vote of the European Parliament in October 2020 to increase the 2030 emission reduction target to 60% compared to 1990. As a response, the EC agreed on increasing the 2030 climate target to -55% GHG emissions compared to 1990, but some of the analyzed scenarios show that a higher target would not only be possible, but also required as to not put too much stress on the years 2030-2050.

The analysis in this paper shows that a wide range of literature and studies exist in the field of energy system modeling targeting the low-carbon transition of the European energy system. The overview of related recent work and the scenario comparison carried out in this paper highlight that, while assumptions and scope of these studies might differ in some points, it is still possible to synthesize common findings and recommendations found across the literature. However, communicating said results to policy and decision makers requires additional effort, as their interpretation is, in most cases, only possible through extensive knowledge of scenario assumptions and/or comparisons. Hence, in Section 5, seven scenarios from three different modeling studies are compared which are all based on a similar set of input assumptions and methodologies. This comparison exercise clearly demonstrates that it is possible to deliver consolidated and robust recommendations for policy and decision makers. It is also noteworthy that the question of how the required strong policy enforcement can be achieved has to be analyzed in more depth. The present analysis only highlights where (and partially what) action is required, yet the particularities of the political process in the EU and its member states needs to be taken into account.

Moreover, the novel, three-dimensional scenario development methodology used for the four openENTRANCE pathways clearly shows that the success of the European energy system transformation is tightly tied to actions in the three dimensions (policy, technology and society) governing also the openENTRANCE scenario generation process. Mirroring the plans set in the EGD against the openENTRANCE results and the scenario comparisons in this paper, consequently, highlights no-regret options for the low-carbon transition but also clearly identified/specified "construction sides" where more ambitious action is required in the different sectors. Exactly these kind of consolidated and converging recommendations and action plans is what practitioners as policy and decision makers as well as stakeholders expect from the research and modeling community.

Chapter 4

Assessment of the stranded assets problem in Europe through myopic foresight

4.1 Introduction and literature review

As a leading economic force, Europe has to play a key role in the transition towards renewable energies. This is supported by the broad amount of research on the topic, especially the electricity sector (Plessmann and Blechinger 2016; Farfan and Breyer 2017; Boie et al. 2016; Jacobson, Delucchi, Bauer, et al. 2017). Coal, as well as other fossil-fuel phase-outs are being enforced across multiple European countries, while ambitious climate goals are being set among members of the European Union (European Environment Agency (EEA) 2018; Council of the European Union 2015). But the lobbying of incumbent actors, as well as a general political inertia, might lead to challenges concerning the fulfillment of set climate goals. As many European countries *already* face overcapacities of energy generation facilities (across multiple sectors), stranded asset problems might arise, potentially disrupting a swift transition towards renewables (Johnson et al. 2015; Caldecott and McDaniels 2014; Bond 2018; Tong et al. 2019).

In general, multiple definitions used in various contexts of stranded assets exist in different fields of study (Caldecott 2018). Through this chapter, we use the definition of stranded assets proposed by Caldecott, Howarth, and McSharry (2013): "stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities".[1] This definition is widely accepted in existing literature regarding stranded assets (Caldecott 2018).

In the last decade, the debate about stranded assets in the energy system gained drastically in importance and consideration. Several recent studies and reports outline this growing relevance. A report from the Carbon Tracker Initiative (Carbon Tracker Initiative 2015) compared the production of coal, natural gas, and oil for all sectors of the International

This chapter is based joint work with Konstantin Löffler, Thorsten Burandt, and Pao-Yu Oei published in *Energy Strategy Reviews* 26 under the title: "Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem". DOI: https://doi.org/10.1016/j.esr.2019.100422; published open access under CC BY 4.0.

[1] For another definition of stranded assets see, for example, the Carbon Tracker Initiative (Carbon Tracker Initiative 2019b).

Energy Agency (IEA) 450ppm with a business as usual scenario. It concluded that no new coal mines are needed, and furthermore that projects with a value of 2 trillion US$ of capital expenditures are in danger to end as stranded assets. A recent study by Mercure et al. (2018) comes to a similar result. They asses future energy demand projections and changes in fossil fuel assets value. Their results show that a substantial fraction of the global fossil fuel industry may end stranded, presenting a total wealth loss of 1-4 trillion US$. In addition, high volumes of valuable resource are being spent unnecessarily. In general, a trend can be identified, where, driven by climate goals, high shares (50-80%) of fossil fuels could become stranded, a phenomenon also known as ”carbon bubble” (McGlade and Ekins 2015).

Previous studies have shown that massive expansions of renewable generation capacities are needed in order to stay within the agreed upon goal of a 2 °C, or aiming at 1.5 °C, mean temperature increase, and that nuclear power is not an economically feasible alternative (Schneider et al. 2018; Kemfert et al. 2017). The issue becomes even more important when considering the SR1.5 of the IPCC (IPCC 2018). Still, new conventional-fueled power plants are constructed across Europe, albeit declining load factors (Eurostat 2018). Therefore, a continuation of current trends has the potential to cause lock-in effects and a severe stranding of assets and resources. Clear signals to prevent such a market failure are missing until now from a policy side (Dessens, Anandarajah, and Gambhir 2016).

Hence, the future investments into the fossil fuel sector, most notably coal, have to be reduced. This is especially important, as Pfeiffer et al. (2016) found that the global capital stock for the power sector consistent with a 50% probability of global warming of 2 °C was reached in 2017. They, and others, conclude that new electricity generation assets must be low-carbon or they may end stranded otherwise (Pfeiffer et al. 2016; Tong et al. 2019). Johnson et al. (2015) conclude similar findings. They emphasize that the construction of coal power plants, especially without installed CCTS technology, would have to be reduced significantly, emphasizing the use of existing capacities over new construction. Also, they argue that both natural gas and coal-based power generation without CCTS have to be phased out to limit the mean global warming to 2 °C and, even more for 1.5 °C. A similar finding regarding natural gas is presented in an article by Hickey et al. (2019) for a distinct regional application. Their study looks into different low carbon scenarios and assesses the utilization of Ireland’s gas distribution network. They conclude that electrification of residential heating can lead to both a reduction of the utilization of the gas network, as well as the risk of large parts of the network being stranded or decommissioned. Furthermore, several cross-sectoral studies conclude overall similar findings (IRENA 2017; Wynn 2016; Carbon Tracker Initiative 2019a; Fitzgerald, Braunger, and Brauers 2019). For example, IRENA (2017) shows high amounts of stranded assets in the buildings sector, mainly due to the slow and inert pace at which changes happen in this sector.

Still, further ignorance of the long-term risks of stranded assets by policy-makers and investors will further increase the aforementioned financial risk. This is also observable in developing countries. Bos and Gupta (2018) look at the risks of investing in fossil fuel infrastructure for China and Kenya. The study finds that investing in renewable energy sources is highly favorable and needed to prevent assets from being stranded. Also, as presented by Green and Newman (2017), the current development and deployment of renewable energy sources have features of disruptive innovation. Such innovation is fast-growing, expands to be a significant disruption to an established system, and inherently leads to stranded assets.

Neglecting long-term risks is often modeled in energy system models using myopic or limited foresight. Notable examples are the studies of Gerbaulet et al. (2019) and Keppo and Strubegger (2010). Both articles limit the foresight of optimization models and feature similar results: A limited foresight leads to limited investments in renewable resources in the earlier modeling periods. This then leads to higher investments and stranded assets in later periods. Another approach was conducted by Fuso Nerini, Keppo, and Strachan (2017). With the help of a modified TIMES model, they analyze the impact of myopic decision making in the energy system of the United Kingdom. They show that myopic planning combined with slow technology diffusion rates could lead to a non-achievement of the climate targets of the United Kingdom. The current aging of the European power plant infrastructure poses chances to transition towards a low-carbon energy system when building renewable energy sources instead of fossil fuel generation capacities (Farfan and Breyer 2017).

Energy system models are widely being used to assess the development and transformation of future energy systems (Hansen, Breyer, and Lund 2019). Jacobson, Delucchi, Bauer, et al. (2017) and Bogdanov et al. (2019) show with their analyses that the global power production can be based on solely renewable energy sources in 2050. Overall, the discussion about the feasibility of 100% renewable energy system (compare Heard et al. (2017) and Brown et al. (2018)) is not the scope of this article. Nevertheless, the studies mentioned above as well as articles by Pursiheimo, Holttinen, and Koljonen (2019) and Deng, Blok, and Leun (2012) conclude that the future energy system should be based on sustainable energy sources. In general, scenarios and models that are assessing future energy systems with large shares of renewables prove to fulfill more sustainable criteria Child et al. 2018; Fuso Nerini et al. 2018; McCollum et al. 2018. In this context, Child et al. (2018) point out, that when considering the constraints of fossil CCTS, it should not be accounted for as a sustainable technology option. Also, Oei and Mendelevitch (2016) conclude in their assessment of CO_2 infrastructure investment that large-scale deployment of CCTS is rather unlikely in Europe.

In general, many studies asses the development of the European power system (Plessmann and Blechinger 2016; Gerbaulet et al. 2019; Steinke, Wolfrum, and Hoffmann 2013; Capros et al. 2014). Even the possibility of a 100% renewable electricity system for Europe is assessed in a study presented by Connolly, Lund, and Mathiesen (2016). They show that 100% renewable power generation is a distinct possibility. Similar findings that no fossil fuels are needed for a flexible energy system were also presented by Child et al. (2019a) recently. Hence, capacity additions of fossil power generation capacities are not needed for the future energy system of Europe.

However, to our knowledge, there is no study that analyzed the issue of stranded assets in the European energy sector while incorporating (electricity, heating, and transportation) sectors. The research question of this chapter therefore assesses the risks of shortsighted capacity planning in the power sector leading to stranded assets within Europe. While most studies include increasing electricity consumption from the heating and transportation sector as exogenous demands, we incorporate these sectors into our analysis to account for inter-dependencies with the power sector. Therefore, this chapter provides a quantitative analysis of the developments of the European energy system for the years 2015 to 2050 in three scenarios, focusing on the issue of stranded assets in the power sector since its implementation in our framework is much more detailed than of the other sectors. A major addition to previous studies is the inclusion of scenarios featuring reduced foresight, as well as current policy trends, in order to quantify the magnitude of the potential stranded asset problem. In doing so, the chapter tries to answer the following research questions: (i) "How does the level of foresight affect capacity expansion in the European power system?" and (ii) "What does shortsightedness in planning mean for potential asset stranding?".

The remainder of the chapter is structured as follows: Section 4.2 pictures the current situation of the European energy system with respect to stranded assets. Section 4.3 briefly explains the model and introduces the scenarios, followed by a discussion of the results in Section 4.4 and a conclusion in Section 4.5.

4.2 Status quo

4.2.1 The current status of the energy system

The ongoing transition of the energy system has led to substantial additions of capacities. Driven by climate targets, fossil fuel cost changes, efficiency gains in renewable energy generation, and a different role of conventional energy, power plants were built despite capacities already being present (Caldecott and McDaniels 2014; Europe Beyond Coal

2018). In turn, higher shares of renewable energies led to a decreasing utilization of gas-fired power generation, even worsening with the trend of installing new capacities. This can be observed in various European countries, like Germany, Italy, the Netherlands, or the UK, where, between 2010 and 2015, the installed capacities of natural gas power plants increased by 10%, while the annual load factor of the same utilities dropped from more than 50% to around 30% (see Figure 4.1). Similar, and in some cases even much stronger, effects are visible in other parts of the world, especially in India and China.

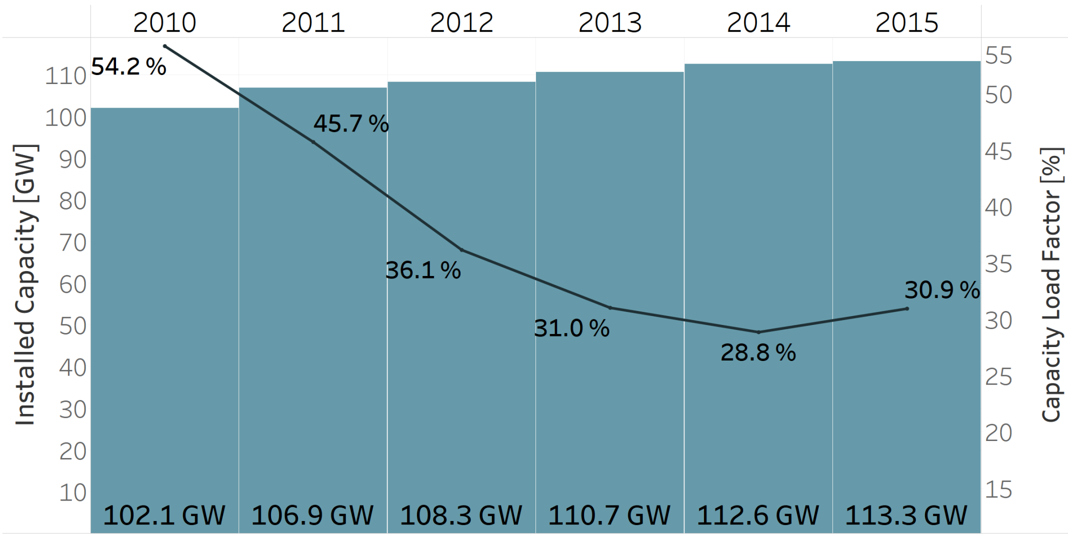


Figure 4.1: Installed natural gas capacities and their yearly load factor for Germany, Italy, UK, and the Netherlands. Source: Own illustration, based on Eurostat (2018) and European Commission (2018c).

When analyzing the dependencies of the single countries with respect to the different conventional fuels, natural gas is mostly used in Italy, the Netherlands, Spain and the UK. Hard coal and lignite coal, on the other hand, are more commonly used in Germany, Poland, and the Netherlands; and the Balkan region, Germany, and Poland respectively.

4.2.2 Current political landscape

The member states of the EU have committed their agreement to the Renewable Energy Directive 2009/28/EC (European Union 2009). Thus, they are obliged to provide their National Renewable Energy Action Plan as well as defining renewable energy targets for 2020. Additionally, a further binding target for GHG emission reduction is adopted for 2030 (European Commission 2018d). Together with the EU's nationally determined contribution

(NDC) to the Paris Climate Agreement (UNFCCC 2015a), each European member state sets explicit targets for their future energy systems GHG reductions.

Still, the political discussion in the EU is twofold: First, some countries are promoting more ambitious climate targets. Most notably, France, Belgium, Denmark, Luxembourg, Netherlands, Portugal, Spain, and Sweden push for enhanced NDCs, and more ambitious climate politics as well as adopting a target for net-zero emission by 2050 (France et al. 2019). Additionally, one of the prominent steps in the direction of creating an *Energy Union* in the EU is the recent decision of the countries Portugal, France, and Spain to develop strategic interconnections (Portugal et al. 2018). Also, in line with the current efforts of the European Commission, they propose to work on accelerating the energy transition by considering cross-border auctions on renewable energy production. Contrary, Hungary, Poland, Slovakia, and the Czech Republic (the so-called *Visegrád Four* countries) agreed on a common stance on the European Union's 2050 climate goals. In the recent negotiations of the European Council on a landmark climate strategy for 2050, the *Visegrád Four*, together with Estonia, protested at the inclusion of the explicit target year 2050 for reaching net-zero emissions. [2]

However, a large share of the countries is currently not on track to meet these targets and thus, substantial acceleration from historical levels is required (Climate Action Network Europe 2018; Clean Energy Wire 2017; Spencer et al. 2017; Ecologic Institute and Climact 2019). This especially includes countries with substantial shares of fossil power generation and high GHG emissions (e.g., Germany or Poland) (Eurostat 2018; ENTSO-E 2018), keeping the global mean temperature increase below 2 °C or even 1.5 °C will be harder to achieve.

Additionally, companies in Germany and Poland are still investing in the refurbishment and construction of coal power plants (Europe Beyond Coal 2018). Other countries that are phasing out coal as primary power generation technology are investing into the construction of additional natural gas power plants (Central European Energy Partners 2019; Smart Energy International 2019) . Although these are less carbon-intense, they will likely end up being stranded as well, if the EU-wide targets for 2050 are enforced (Hainsch et al. 2018; ECA 2015).

As an example, Germany was one of the leading countries for transforming their energy system within the frame of the so called *Energiewende* (Krause, Bossel, and Müller-Reissmann 1980; Hirschhausen et al. 2018).[3] This rapid addition of RES was mainly made possible

[2] See https://www.euractiv.com/section/climate-strategy-2050/news/eu-climate-deal-falls-at-summit-four-countries-wield-the-axe/; last accessed 25.04.2021.

[3] The term *Energiewende* has its roots in the environmental and anti-nuclear movements in the 1970s in Germany. Krause, Bossel, and Müller-Reissmann (1980) coined the term with their book, laying out

by to the German Renewable Energy Sources Act (EEG) (Bundesministerium der Justiz und für Verbraucherschutz (BMJV) 2014) which lead to a significant increase of RES in the electricity sector from 7% in 2000 to nearly 36% in 2017 (BMWi 2018). Albeit this significant change in the power sector, limited success of decarbonizing the other sectors, i.e. heating or transportation, and current policy changes regarding RES expansion make it likely that Germany will fail to reach. the 2020 EU target (Clean Energy Wire 2017; Oei 2018).

A further issue might be the strong influence of the energy industry on the policy- and decision-makers (Haas 2017; Kungl and Geels 2018). Together with other interest groups, like labor unions and other affected energy intensive industry branches (e.g. the steel industry), the lobby for conventional energy sources has a prominent effect on the current politics and, therefore, on the pace of transforming the energy system (Cadoret and Padovano 2016). Another significant barrier which might lead to a failure of the 2020 GHG targets are considerations of national (energy) security and other idiosyncrasies (Jonsson et al. 2015). Hence, populist governments are less likely to promote RES than left-wing ones (Cadoret and Padovano 2016)).

4.3 Model and data

The model utilized in this study is the Global Energy System Model (GENeSYS-MOD), an open-source linear optimization model, encompassing the sectors electricity, heat, and transport of the energy system.[4] For information on the general model formulation and the European dataset, see Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) and Burandt, Löffler, and Hainsch (2018). A stylized graphical representation of the model can be seen in Figure 4.2.

Europe is divided into 17 nodes, each representing a country or geographic region. Demands for electricity, passenger & freight transport, as well as for low- and high-temperature heat are given exogenously via scenario assumptions (see Burandt, Löffler, and Hainsch (2018)), with the model seeking to meet the required energy demands in each time slice. To achieve this, the model calculates the optimal capacity investments into generation and storages, the usage of sector-coupling technologies, and thus the resulting energy mix.

paths for a transformation of the energy system. Since then, the term has been frequently associated with the German energy transition, also outside of Germany.

[4]GENeSYS-MOD is based on the Open Source Energy Modeling System (OSeMOSYS) and further expands its features.

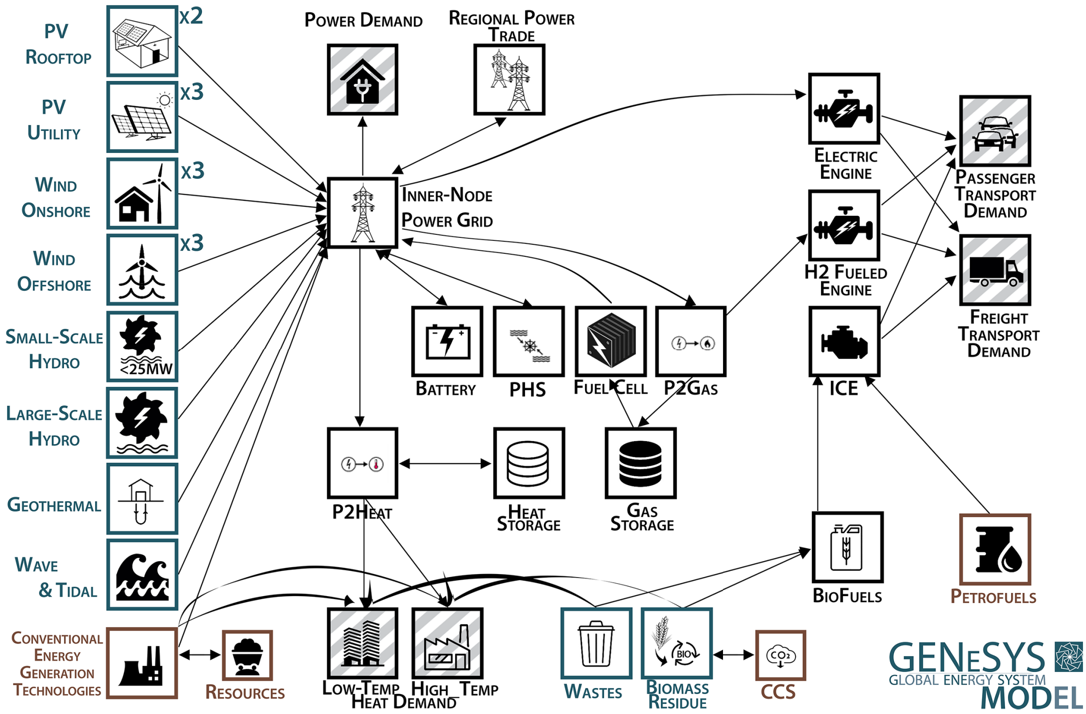


Figure 4.2: Model structure of GENeSYS-MOD v2.0. The model differentiates between two different kinds of rooftop PV (residential, commercial), and three categories of utility PV, onshore, and offshore wind (optimal, average, and inferior for utility PV and onshore wind; shallow, transitional, and deep for offshore wind). Source: Own illustration.

To analyze the amount of stranded assets and impact of delayed policy measures, multiple scenarios have been defined.

Scenario 1. **BASE**: Follows the baseline scenario of Hainsch et al. (2018), staying below a 2 °Celsius climate target with a resulting CO_2 budget of 51.97 $GtCO_2$ for Europe for the years 2015 - 2050. Emissions are distributed endogenously, and the cost-optimal pathway is calculated based on a social planner's perspective with perfect foresight.

Scenario 2. **RED**: Introduces reduced foresight to the model. The calculations only encompass a limited time horizon of 5 years (which might correspond to the limited perspective of election periods of 4-5 years or some business concepts). The model optimizes the energy system for 2015, 2020, and 2025 with reduced foresight, taking the resulting production values and constructed capacities of the previous optimization step as given. After 2025, the model optimizes the pathway towards 2050, trying to uphold the 2 °C limitations.

Scenario 3. **POL**: Adds additional political constraints to the reduced foresight scenario. Since real-life policy decisions are not always cost-optimal, and instead driven by lobbying groups, incumbent actors, and interested parties, the current political landscape, as described in section 4.2.2, is taken into account. It is assumed that regional targets for renewable energies (see European Environment Agency (EEA) (2018)) are not overachieved, thus representing an upper barrier for the model. Also, existing conventional generation lifetimes are extended as a policy measure. Again, starting at 2025, the model realizes the importance of the 2 °C target and starts the regular optimization process (cost-minimizing; upholding climate constraints) from 2030 onward.

Common for all scenarios is a carbon budget of 51.97 $GtCO_2$. This budget is calculated by using the global carbon budget found in the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC 2015). Updated calculations with a changed methodology have resulted in different higher CO_2-budgets within the 1.5SR. The chosen budget of 51.97 Gt CO_2 is therefore equivalent to a 2 °C target (with respect to the older estimations) or a below 2 °C target (with respect to the newest estimations). Exogenous emissions (such as cement production or LULUCF) that are not included in GENeSYS-MOD are further excluded from this budget. The remaining amount is then distributed to the modeled region by using the population as an indicator. A graphical representation of the process can be found in Appendix B. For further information, refer to Burandt, Löffler, and Hainsch (2018).

The computational process of the reduced foresight analyses is depicted in Figure 4.3. The model computes the optimal capacity investments and energy mixes *at that specific point in time* and uses these results as given decisions of the past when conducting the next optimization step.

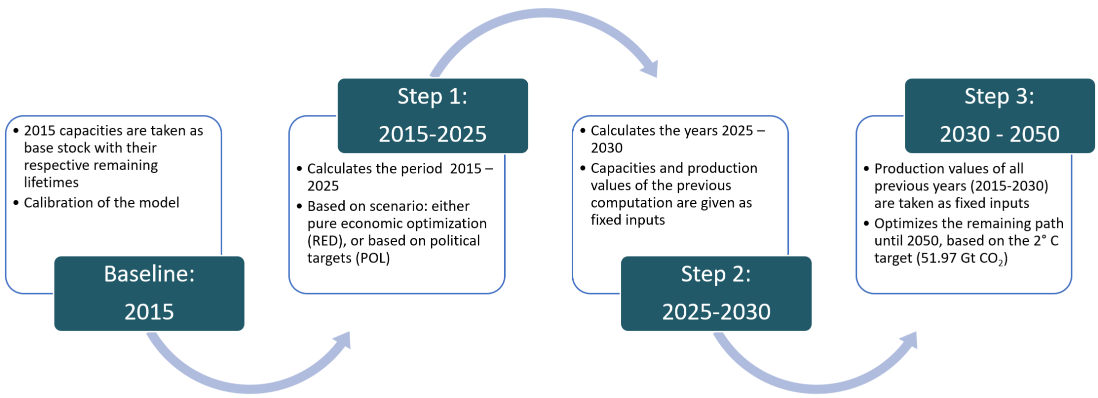


Figure 4.3: Computational process of the reduced foresight scenarios (RED & POL). Source: Own illustration.

4.4 Results

The model results show that reduced foresight does affect the short-term decision making process when it comes to long-term goals such as climate targets. This effect is further increased if political drivers delay, or even prevent, the theoretically cost-optimal measures. Adherent to that, the RED scenario shows a total cost increase of about 5% in total system costs. The POL scenario is the most expensive, with an increase of 6.2%. This is due to additional assets being built, but quickly becoming obsolete when a strict CO_2 target is implemented. The costs of the implemented lifetime extensions of the POL scenario are however, not included in the scenario run and therefore would even worsen the comparison. All three scenarios manage to uphold the below 2 °C goal, and are thus *technically* feasible, but the shorter planning horizon leads to shifts in energy use and a swifter need for emission reduction in the later years, which, in turn, leads to an increase in unused capacities and stranded assets. Figure 4.4 shows the changes in the relative primary energy mix for the years 2020, 2030, 2040, and 2050. The scenarios running under reduced foresight both see an increased utilization of natural gas, as well as lignite until 2040. Compared to the BASE scenario, natural gas serves as more of a bridging technology (mainly in the heating sector), whilst the BASE case sees a swifter transition towards RES, especially onshore wind energy. Nuclear is more prominent in the POL scenario, where politically driven lifetime extensions keep nuclear in the mix. Due to the heavily increased emissions in the earlier periods, bio-energy with carbon capture, and storage plays a role in the POL scenario as negative emission technologies are needed in order to facilitate the achievement of climate goals.

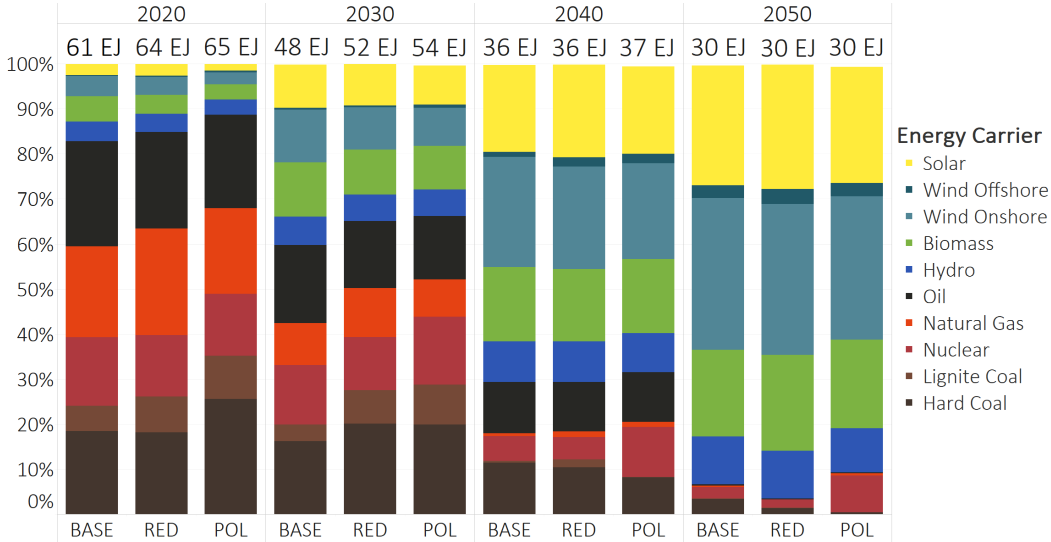


Figure 4.4: Primary energy supply for the years 2020, 2030, 2040, and 2050, both relative, as well as total amount in Exajoule (EJ). Source: Own illustration.

Figures 4.5 and 4.6 show the unused generation capacities resulting from the model calculations. A clear distinction between the three scenarios can be made, with POL consistently showing the highest amounts of unused generation capacities.

From a geographical standpoint, regions with high amounts of natural gas- and/or lignite coal capacities face the biggest challenges when strict decarbonization goals are enforced.

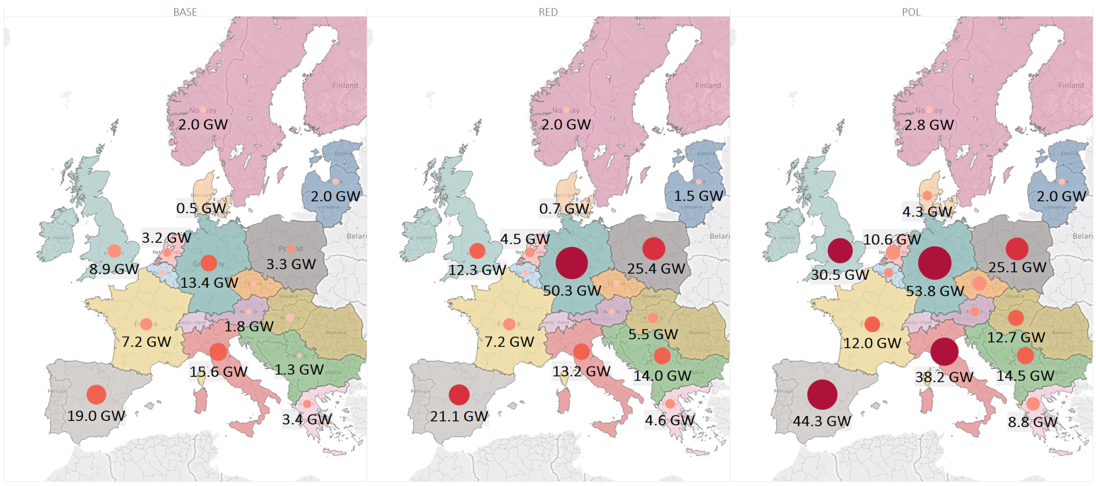


Figure 4.5: Total stranded assets for coal- and gas-fueled power generation per region in the year 2035. Source: Own illustration.

Under reduced foresight, especially cheap and local power from lignite is preferred in the short-term, leading to (stranded) overcapacities in the later years (when climate targets become binding). The lifetime extensions of the POL scenario further increase this effect, leading to vast amounts of underutilized plants. As depicted in Figure 4.6, around 120 GW of hard coal and lignite coal are unused in 2035 in the POL scenario as compared to 6.7 GW in the BASE scenario. Using the capital costs of 1600 € per kW for hard coal and 1900 € per kW for lignite coal respectively, 105 billion € of capital are stranded by 2035. This amount significantly increases to 200 billion € when taking the 145 GW of unused gas-fired capacity into account.

The RED scenario sees a similar high amount of stranded capacity of coal and gas with 87 GW coal and 110 GW gas-fired in 2035, corresponding to around 150 billion €. Only in the BASE scenario with perfect foresight, the amount of unused capacity (with the inherent risk of stranded capital) is significantly reduced. In 2035, the BASE scenario sees 76 GW of unused gas capacities in addition to the aforementioned 6.7 GW in coal assets. This equals an an amount of 50 billion € 67% less than in the RED and 75% less than in the POL scenario, respectively. This showcases the importance of long-term planning and decision making when climate goals are to be enforced.

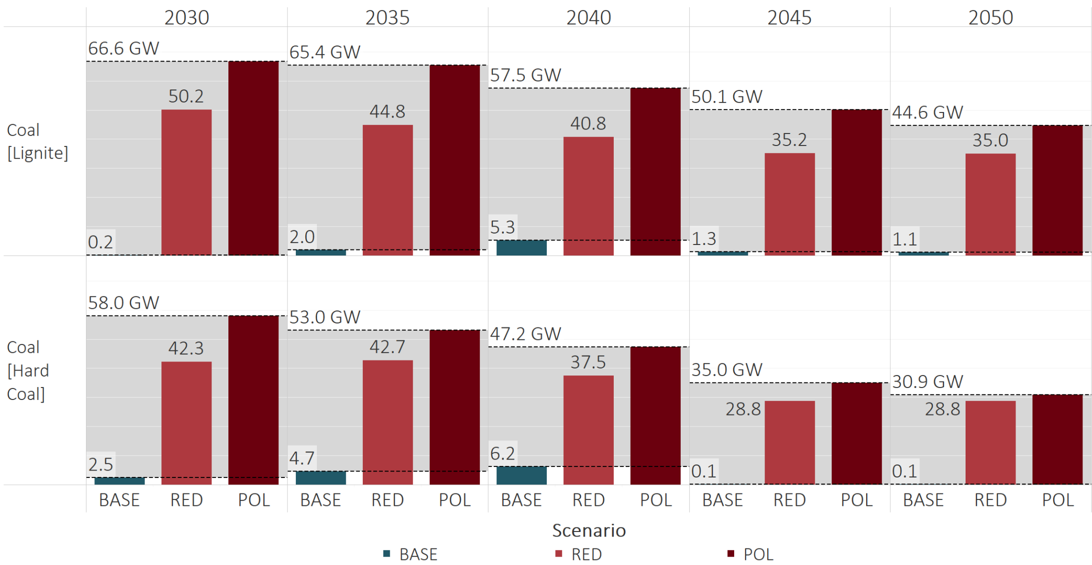


Figure 4.6: Total amount of unused capacities for coal-based power plants. Source: Own illustration.

Figure 4.7 shows the development of total gas-fired generation capacities, as well as their load factor for all three scenarios until 2040. In the medium term (2020-2039), gas-based power plants are most commonly used in the BASE scenario, where they serve as a relatively low-emission alternative to coal- and lignite-based generation. They are also partially used in conjunction with bio-gas, reducing their emission intensity even further. POL sees the highest installed capacities, but also the lowest utilization factors for the gas plants. Comparatively expensive gas is replaced by cheap coal, reducing the load factors. After 2035, with the sudden 'realization' of urgent need for climate action (see the scenario descriptions in section 4.3), fossil gas cannot be utilized due to extremely tight carbon constraints, causing load factors to decline even further.

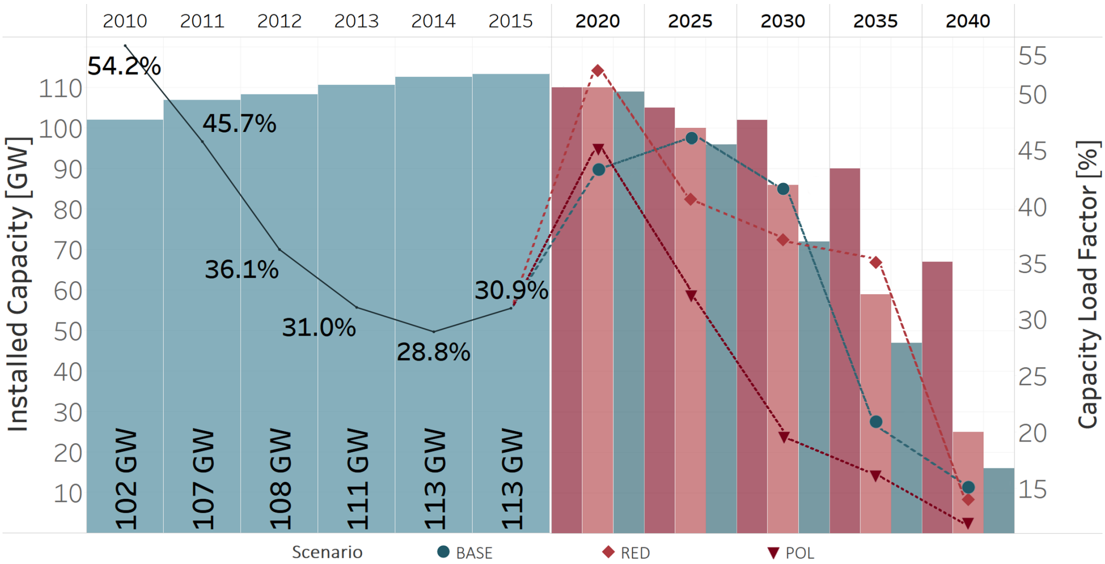


Figure 4.7: Gas power plant capacities and load factor for Germany, Italy, UK, and the Netherlands. Source: Own illustration, data for 2010-2015 based on Eurostat (2018) and European Commission (2018c).

Having to meet a CO_2-budget in line with the 2 °C climate target, a shift in emissions between the different sectors and time periods can be observed for the three scenarios. Figure 4.8 shows the difference in emissions per sector, compared to the BASE scenario.

Especially in the earlier years of the modeling horizon (where the reduction of foresight takes place), emissions are vastly higher in the electricity sector. The overall system cost is increased due to having to match these shortfalls in the earlier periods with additional decarbonization measures in the heat and transport sectors, mostly in the form of bio-fueled options and a shift from coal to gas in the heating sector. In the later years, most of the shift in emissions lies in the heating and power sectors.The only way to achieve the carbon budget for the POL scenario is by using costly negative emission technologies, which additionally comes with severe other social and environmental issues (Minx et al. 2018; Fuss et al. 2018).[5]

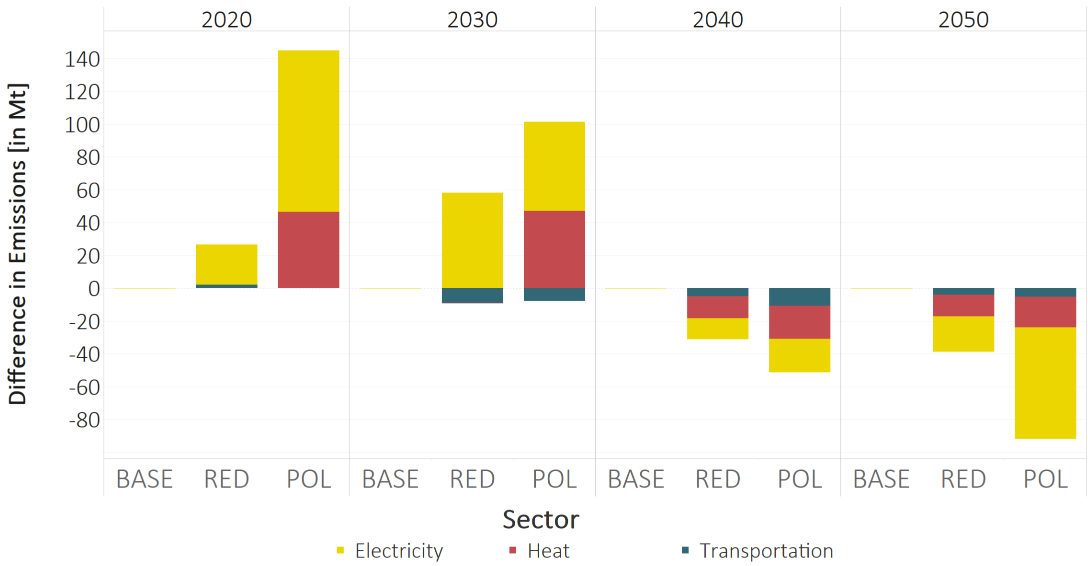


Figure 4.8: Emission differences between scenarios for the sectors electricity, heat, and transportation in Mt CO_2 in comparison to the Base scenario. Source: Own illustration.

Social cost analysis While potential stranded capacities and investments of businesses are an important concern about moving forward with the low-carbon transition, policy makers should also factor in social costs and benefits in their decision making process. The burning of fossil fuels causes significant damage to health and environment. A recent study of the German *Umweltbundesamt* (the German Environment Agency) shows that an internalization of such negative externalities would raise the necessary carbon price to about 180€/tCO_2 (Matthey and Bünger 2019).

Figure 4.9 shows a sensitivity analysis of levelized costs for key technologies with regard to different CO_2 prices by comparing the social cost value of 180€/tCO_2 to the current EU Emissions Trading System (ETS) price (29€/tCO_2 in August 2019[6]). It can be clearly demonstrated that given a carbon price that reflects the actual damages, renewable technologies provide the cheapest source of electricity. This holds true even for already operational fossil-fueled plants (e.g. the capital cost part being zero). With the predicted decline in capital costs for renewable technologies in the upcoming years (see Appendix D), this

[5] Also, methane leakage is not included in the scope of the model when considering CCTS technologies.
[6] See https://markets.businessinsider.com/commodities/co2-european-emission-allowances; last accessed 25.04.2021.

effect is even increased, with some RES already being the cheapest form of electricity even at relatively low CO_2 prices.

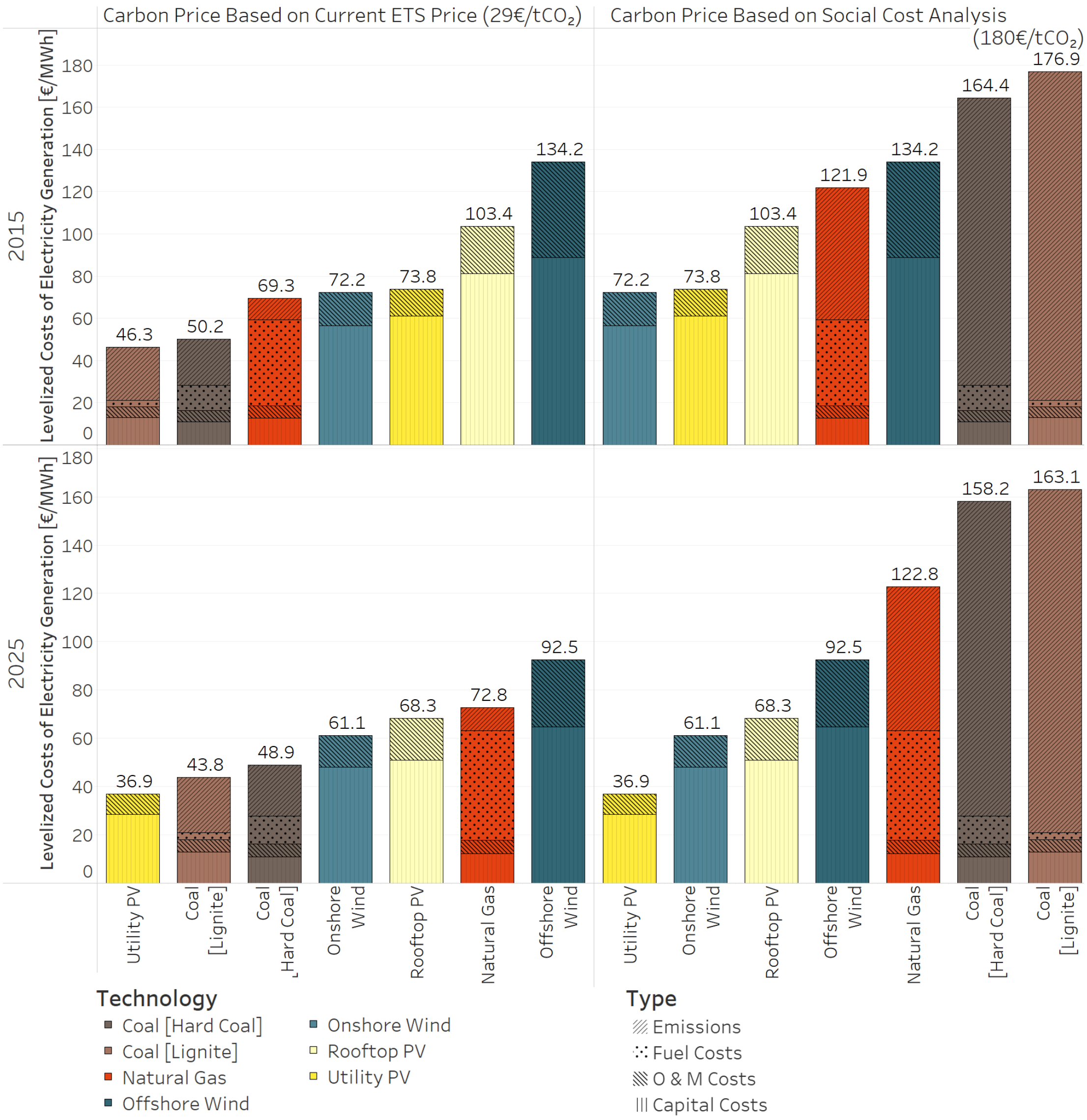


Figure 4.9: Levelized cost analysis for key technologies (Average across the modeled regions). Levelized costs are computed given for two different CO_2 prices: left shows the merit order for a CO_2 price based on current European Emissions Trading System (ETS) prices, whereas the right-hand side shows a CO_2 price based on an internalization of negative external effects (Matthey and Bünger 2019).

This means that constructing new renewable power plants would actually be cheaper (from a social benefit standpoint) than using the existing fossil-fueled power plants. This finding further underlines the previous results, highlighting that when long-term climate goals (which align with social welfare improvements) are prioritized over short-term decision-making, no additional investment in new or existing fossil power plants should be done. Also, implementing policies that maximize social benefits (by minimizing social costs), such as implementing a CO_2 price that reflects the actual negative externalities, would achieve the necessary effects and drive fossil generators out of the market (as long as fossil subsidies do not distort these market characteristics).

4.5 Conclusion

The European energy system is on the brink of change. To achieve the ambitious climate goals, a transition of the energy system away from fossil fuels and towards renewable energy sources is needed. However, there is an ongoing debate about the actual implementation of possible pathways and the challenges involved. Substantial capacity additions over the last few years, coupled with changes in capital and fuel costs, energy efficiency gains, and a different role of conventional energy, have led to overcapacities already being present in the energy system (Johnson et al. 2015; Caldecott and McDaniels 2014; Bond 2018). While an omniscient, cost-optimizing planner is often used in optimization models, real-life decisions are usually based on incumbent parties, political influence, and imperfect foresight (Haas 2017). This chapter introduces two new scenarios, *RED* and *POL*, featuring reduced foresight for the years up until 2030. The POL scenario also includes political boundaries, representing the imperfect decision-making process of policy makers that often have to compromise. These boundaries include the assumption that national targets for renewable integration will not see an over-achievement, and lifetime extensions for conventional capacities (due to incumbent actors exerting their power, fear for job losses, and energy security concerns).

The results show that there could be massive amounts of unutilized -and thus stranded - capacities in Europe in the upcoming years if climate targets are taken seriously. The BASE scenario, which includes perfect foresight out of a social planner's perspective, already sees substantial amounts of stranded capacities in the medium term if a climate target of below 2 °C is to be met (roughly 85 GW in stranded capacities, corresponding to about 50 billion € in investment losses). Introducing reduced foresight similar to short-sighted political and business strategies to the model further increases this problem, as it leads to an over-construction of conventional generation capacities in the 2020s that quickly become obsolete and underutilized (RED scenario: 150 billion €, POL scenario: 200 billion €).

The decreasing competitiveness of conventional energy generation poses difficult challenges for investors, owners, and policy makers, as issues such as stranded assets and job security arise. Also, forcing premature shutdowns of generation facilities often leads to legal disputes about damages due to profit losses by the generators (such as currently being seen in Germany with nuclear power providers[7] and the coal commission findings (BMWi 2019)). However, additional results from a social cost analysis show that environmental and health damages, when considered, heavily influence the cost-competitiveness for fossil-fueled power plants. This further increases the need for strong and clear signals from policy makers, which are needed to prevent construction of unnecessary fossil-fueled power plants and combat the threat of investment losses and wasted resources that could increase significantly when short-term goals are prioritized over long-term targets. Further research is required for the issue of stranded assets in other sectors or regions, which are not covered by our work.

[7] See https://www.dw.com/en/german-government-approves-nuclear-phaseout-compensation/a-43892394; last accessed 25.04.2021.

Part II

GERMANY'S ENERGY SYSTEM TRANSFORMATION: CHANCES AND BARRIERS, CHALLENGES, AND POLICIES

Chapter 5

Model comparison on the German energy system transformation

5.1 Introduction

The European Climate Law as part of the European Green Deal paves the path to climate neutrality by 2050. A central target is the reduction of GHG emissions of at least 55% until 2030, compared to 1990 levels (European Commission 2021). In order to meet these European targets, Germany as a EU member state is constantly adjusting its climate action plans. A 2021 study by an influential think tank in Germany proposed to even go beyond EU regulations to reach climate neutrality five years earlier by 2045 (M. Weiß, M. Wünsch, and I. Ziegenhagen 2021). This target has been adopted by the German government shortly after its publication, including a reduction of GHG emissions of at least 65% until 2030 (Die Bundesregierung 2021).
In order to reach the necessary emission reductions, the German energy system needs to transition from fossil fuels towards renewable energy sources. However, in 2019 only a small share of 17.4% of the German gross energy consumption was covered by renewable energy sources (Umweltbundesamt 2021). This picture changes when focusing solely on the power sector. The renewable share of gross electricity generation reached 42% in 2018 (Umweltbundesamt 2021). Despite this achievement, the power sector only accounted for 20.6% of the total energy consumption in 2018 (BMWI 2020). For the decarbonization of all sectors, the power sector will become more and more important. Its share of the total energy consumption is expected to rise in the coming decades with the emergence of sector coupling through electrification options in the other energy sectors. For a scenario reaching 100% renewable energy supply, it is estimated that the current yearly electricity demand will almost double to over 1000 TWh (M. Weiß, M. Wünsch, and I. Ziegenhagen 2021). Decarbonizing the power sector primarily demands an extensive expansion of VRE generation capacities. The main renewable energy sources available in Germany

This chapter is based joint work with Jonas van Ouwerkerk, Soner Candas, Christoph Muschner, Stefanie Buchholz, Stephan Günther, Hendrik Huyskens, Sarah Berendes, Konstantin Löffler, Christian Bußar, Fateme Tardasti, Luja von Köckritz, and Rasmus Bramstoft published in *Renewable and Sustainable Energy Reviews* 161 (2022) under the title: "Comparing open source power system models - A case study focusing on fundamental modeling parameters for the German energy transition".DOI: https://doi.org/10.1016/j.rser.2022.112331; published open access under CC BY 4.0.

are solar PV, wind onshore, and wind offshore. In recent scenario calculations from several studies their assumed potential varies between 99-550 GW, 83-180 GW, and 20-70 GW, respectively (Dena 2021; M. Weiß, M. Wünsch, and I. Ziegenhagen 2021; Luderer, Kost, and Sörgel 2021). To bring demand and supply from these VRE sources into balance, additional flexible technologies are required. Storage systems can serve this purpose by shifting energy in time. A study estimates that the storage capacity demand for Germany needs to be substantially increased in systems with high shares of renewable generation (F. Cebulla, T. Naegler, and M. Pohl 2017). In addition to temporal flexibility, the power system requires spacial flexibility. The efficient distribution of local generation from VRE demands a substantial expansion of electricity grids. On a European level, the expansion of transmission capacities between countries plays an important role. However, for Germany, already substantial transmission capacities exist to neighboring countries and therefore they only need to be expanded by small margins towards 2050 (Child et al. 2019b). On a local level within Germany, however, transmission capacities have to be greatly expanded to balance geographically distributed generation from VRE (50Hertz Transmission GmbH et al. 2021).

5.1.1 Towards EU and German climate policy goals

The Paris climate agreement from 2015 sets ambitious goals regarding the reduction of GHG emissions for countries around the world (UNFCCC 2015b). Consequently, the EU is in charge to ensure that all its member states take the appropriate actions to achieve the agreed targets. As a major cornerstone of European climate politics, the European Green Deal aims at transforming the EU towards, among others, climate neutrality in 2050, as well as a reduction of GHG emissions of 55% compared to 1990 levels (European Commission 2019a).

To address this pledge towards climate protection and neutrality, the German government adopted the climate protection act in 2020 (Die Bundesregierung 2019). Among others, the government planned to reduce primary energy consumption by 50% compared to 2008 levels, aiming for 65% and 80% renewable shares in gross electricity production by 2030 and 2050, respectively (Die Bundesregierung 2018). Regarding emissions, targets were set to reduce emissions by 55% until 2030 and achieve 80 to 95% reduction, or even carbon neutrality, by 2050 (Die Bundesregierung 2019). In April 2021, however, the 2020 climate protection act was partly deemed to be unconstitutional by the federal constitutional court as it infringes Basic Law (Bundesverfassungsgericht 2021). The act lacked clarity on measures how the goals should be achieved beyond 2030 and disproportionately put the burden of emission reduction on future generations (Bundesverfassungsgericht 2021). The submitted update changes greenhouse gas reduction targets by raising the 2030 and 2040 target to 65% and 88% compared to 1990 levels, respectively, and achieve carbon neutrality by 2045 (BMU 2021a). Additionally, GHG-reduction targets for the different sectors (energy, industry, transport, buildings, agriculture and others) until 2030 were redefined, especially increasing the pressure on the energy sector.

Still, some of the German climate targets, such as the share of renewable generation in gross electricity production, are ranked as 'highly insufficient' to achieve the Paris Agreement goal to limit global warming to well below 2 degrees by 2050 (Climate Action Tracker 2022). A number of studies already showcase the viability of an energy system based on 100% renewable energy, focusing on the rapid expansion of renewable power generation capacities and sector coupling (Bartholdsen et al. 2019; Henning and Palzer 2012; Göke et al. 2021). As a consequence, the newly appointed government that was elected in December 2021 agreed on much more ambitious climate targets in certain areas for the year 2030, like increasing the share of renewable energy in gross electricity production to 80%, aiming for a phase-out of all coal power plants, and drastically increasing the number of electric vehicles to 15 million (SPD, Bündnis 90 / Die Grünen, and FDP 2021). While the new government aims to put Germany on a pathway compatible with a 1.5 °C climate target (SPD, Bündnis 90 / Die Grünen, and FDP 2021), various experts and institutes already pointed out the insufficiency of the agreed measures (Quaschning et al. 2021; Kemfert 2021).

5.1.2 Challenges in power system modeling

Power system models, which are a subset of energy system models, have proven to be useful tools in helping decision makers to take concrete steps to, among others, define renewable and emission reduction targets. Therefore, it is expected that they can deliver reliable and robust results of the highest quality. Despite most models being capable of answering a wide range of policy questions, there are many obstacles in complexity, transparency, and standardization that still need to be addressed (Savvidis et al. 2019). Consequently, a strong movement within the research community has emerged that can be summarized as Open Science practices. Open Science practices contribute to increasing transparency, reproducibility, and quality (TREQ) of software based research (Huebner, Fell, and Watson 2021). open source software (OSS) is a prerequisite of Open Science and has led to the development of a large number of open source power system models (OSPSM) within recent years. The OS approach aims to accelerate the availability of the latest modeling approaches and to guarantee high quality results. Another important aspect of OS is that it encourages greater collaboration between modelers with different backgrounds

(Vicente-Saez and Martinez-Fuentes 2018), thus improving the quality of the power system models through re-use of data and source code. The potential for greater transparency and availability achieved through OS is increasingly recognized as a fundamental aspect of funded science. Consequently, funding agencies such as the EU Commission or the German Federal Ministry for Economic Affairs and Energy have increasingly promoted Open Science practices in recent years.

Since power systems and their future concepts become more and more complex, new diverse modeling approaches aim to improve performance and results (Savvidis et al. 2019). At the same time, it becomes increasingly difficult to keep up with the latest model developments from a policy perspective. For this reason, there are several studies that compare different power system models (Cebulla and Fichter 2017; Ringkjøb, Haugan, and Solbrekke 2018; Gacitua et al. 2018; Groissböck 2019; Savvidis et al. 2019; Ridha, Nolting, and Praktiknjo 2020; Klemm and Vennemann 2021; Gils et al. 2019; Siala et al. 2020) most of which are not Open Source. They can be grouped into two main categories. The first group of studies (Cebulla and Fichter 2017; Ringkjøb, Haugan, and Solbrekke 2018; Gacitua et al. 2018; Groissböck 2019; Savvidis et al. 2019; Ridha, Nolting, and Praktiknjo 2020; Klemm and Vennemann 2021) exclusively focuses on differences in modeling approaches of power system models from a theoretical point of view. This includes mathematical formulations, spatial and temporal resolutions, applicability, and others. Groissböck (2019) especially focuses on OS versus commercial models, confirming the maturity of Open Source. The second, smaller group of studies (Gils et al. 2019; Siala et al. 2020) performs a scenario analysis to compare the results of different power system models. While Siala et al. (2020) compare model features like type (optimization, simulation) and resolution (temporal, spatial) in a European decarbonization pathways scenario towards 2050, Gils et al. (2019) analyze model load balancing and sector coupling with single year scenarios for 2050 in Germany. In both groups, only the minority of the models used are Open Source. More information about the studies' main findings are summarized in Table 5.1. We conclude that in literature, a comprehensive Open Source comparison of solely OSPSM with a detailed scenario set-up and fully harmonised input data set does not exist to the best of our knowledge.

5.1.3 Contributions

With our work, we aim for a profound comparison of five OSPSM by modeling the transition of the German power system with eight single-year scenarios. The selection of contributing models is characterized by a variety of modeling approaches that allow for a well-founded model comparison. However, our scenario set-up is chosen to go beyond a simple comparison. With the variation of key modeling parameters and characteristics, that are relevant to

Table 5.1: Content summary of studies.

Group I	**Study**	Total models in study	Of which are OS
Cebulla et al. investigate the influence of LP and MILP power plant modelling on storage deployment and expansion in an energy system with a high share of renewables. They find that LP modeling leads to a lower storage expansion and utilization compared to MILP and that MILP modeling is superior in considering storages realistically.	Cebulla and Fichter (2017)	1	0
Ringkjøb et al. review 75 modelling tools to provide an updated overview of their theoretical potentials and differences using a category system. They identify future challenges amongst others openess and transparency.	Ringkjøb, Haugan, and Solbrekke (2018)	75	24
Gacitua et al. theoretically review planning models for power generation expansion and their suitability for energy policy analysis. They highlight methodological differences and modelling challenges.	Gacitua et al. (2018)	21	4
Groissböck reviews open source energy system optimization tools on 81 functions for their maturity. He concludes that open source tools are ready, but just like commercial programmes, they need to constantly adapt to the challenges of new energy systems.	Groissböck (2019)	31	26
Savvidis et al. examines model comparison schemes and propose a set of comparison criteria to cluster energy policy questions to quantify the gap between model capabilities and policy questions. They identify lagging model features and set priorities for future energy system modelling funding.	Savvidis et al. (2019)	41	14
Ridha et al. review 145 energy system models regarding their complexity and cluster them on their purpose and underlying research questions.	Ridha, Nolting, and Praktiknjo (2020)	145	n/a
Klemm et al. evaluate existing energy system modelling tools and identify typical model characteristics to optimise city level systems. They introduce a category system and conclude that only a fraction of the models is suitable for energy system optimisation at city level	Klemm and Vennemann (2021)	13	5
Group II			
Gils et al. present a systematic model experiment on a German case study. In addition to theoretical model differences they strive to link result differences to model differences and quantify their impact. Due to the nature of their experimental design, this is difficult to do and future modelling decisions are deduced to enable this.	Gils et al. (2019)	4	1
Siala et el. conduct a model experiment to assess the impact of four major model features on the results. The impact of each feature is analysed in an isolated experiment and a high level of data harmonisation is applied.	Siala et al. (2020)	5	1

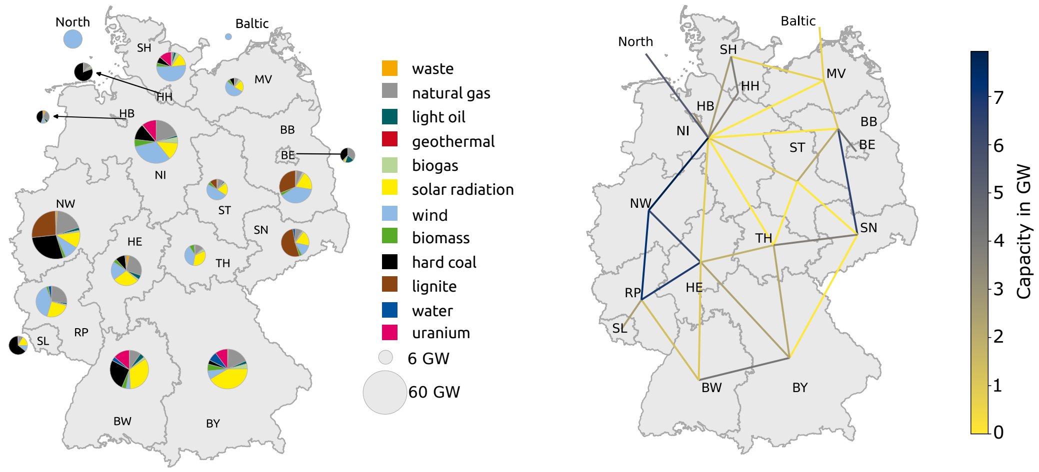
model policy relevant targets, we aim to evaluate their influence on optimal system configurations, for all participating models, respectively. Furthermore, the proposed policy targets for 2030 by the new German coalition, that was elected in December 2021, are applied in all models to show overall trends that may arise for the optimal system. However, it is important to note, that with our scenario scope and analysis we do not intend to evaluate any of the political measures and targets in depth, since simplifications of our models in terms of the harmonization process are inevitable. To address the challenge of data harmonization, we use a novel OS data model connected to the Open Energy Platform (OEP) database (Open Energy Family 2022), which serves as a central repository for accessing the scenario data and uploading the results. Scenario data, modeling results, as well as the connectors between the participating OSPSM and the OEP are made publicly available to emphasize the Open Science characteristics of this study.

5.2 Scenario definition and methodology

In our model comparison, we focus on the transition of the German power system by applying eight one-year scenarios to five selected OSPSM. Subsection 5.2.1 presents the definition of the scenarios and highlights modeling choices. The contributing OSPSM and their respective model configurations are described in Subsection 5.2.2. In Subsection 5.2.3 we explain our model and data harmonization procedure in detail.

5.2.1 Scenario definitions

The geographical scope of all scenarios in this study is Germany, which is made up of 16 federal states. The historical generation capacities for each federal state in 2016, obtained from Bundesnetzagentur (2021), build the foundation for all scenarios (brownfield approach). Figure 5.1a illustrates the generation capacities in each state categorized into primary input energy. In addition to generation capacities the data set consists of basic techno-economic power plant characteristics, which includes efficiencies, costs, and lifetime. The federal states are further interconnected with AC-transmission lines. Their capacities are calculated using historical data from Matke, Medjroubi, and Kleinhans (2016) and Platts (2020) (Figure 5.1b). Moreover, we define a transmission line to offshore wind farms in the North Sea (North-link) and offshore wind farms in the Baltic Sea (Baltic-link). Transmission interconnections with neighboring countries are not considered in the scenario set-up. However, exogenous historical and future hourly export and import trades with neighboring countries are taken from the European power system model calculated in Gawlick, Kuhn, and Hamacher (2020) and are added to (or subtracted from) the demand of adjacent federal states. Existing capacities for batteries and pumped hydro storage in 2016 are included in the base set-up of all scenario. Figure 5.1 summarizes the base set-up while Table 5.2 gives an overview of the technology portfolio. Access to the full input data set and data sources is provided in the data availability section of this manuscript.



(a) Generation capacities (b) Transmission capacities

Figure 5.1: Historical capacities of 2016 for generation and transmission that are the basis of all scenarios. The federal states are: Brandenburg (BB), Berlin (BE), Baden-Wurttemberg (BW), Bavaria (BY), Bremen (HB), Hessen (HE), Hamburg (HH), Mecklenburg-West Pomerania (MV), Lower Saxony (NI), North Rhine Westphalia (NW), Rhineland Palatinate (RP), Schleswig-Holstein (SH), Saarland (SL), Saxony (SN), Saxony Anhalt (ST), and Thuringia (TH).

Table 5.2: Overview of technologies portfolio.

Energy conversion		**Storage**	**Transmission**
Hard coal steam power plant	Nuclear power plant	Battery storage	HVAC transmission
Hard coal steam CHP plant	Waste steam power plant	Pumped hydro storage	DC transmission
Lignite steam power plant	Waste CHP power plant	Hydrogen cavern storage	
Lignite steam CHP plant	Biogas combustion engine plant	Hydrogen gas power plant	
Gas power plant	Biomass steam power plant	Alkaline electrolyzer	
Combined cycle gas plant	Wind turbine onshore		
Combustion engine gas plant	Wind turbine offshore		
Gas CHP power plant	Photovoltaic rooftop		
Combined cycle CHP gas plant	Photovoltaic utility		
Combustion engine CHP gas plant	Geothermal power plant		
Light oil power plant	Run-of-river power plant		
Light oil CHP power plant			

CHP - combined heat and power; HVAC - high-voltage alternating current; DC - direct current

By adding additional constraints to the base set-up, we create specific scenarios for the model comparison for the years 2016 and 2030 (Figure 5.3). In all scenarios, hourly electricity demands are taken from Löffler, Burandt, and Hainsch (2021) and Löffler et al. (2022). For 2030, this includes future exogenous demands from the (partial) electrification of the industry, buildings, and transportation sectors (Figure 5.2). Expansion potentials for solar

PV and onshore wind are calculated by using the pyGRETA tool (Siala et al. 2020) by aggregating high-resolution spatial data for each German federal state. This calculation is based on MERRA-2 Reanalysis weather data from 2017 and it uses geospatial data for the land use (cropland, settlement, marsh, etc.), topography, slope, and distances to urban regions. For the offshore wind expansion, a limit of 50 GW is set, which is a conservative assumption and slightly lower than the limit given in Luderer, Kost, and Sörgel (2021). We assume that all those renewable potentials can be fully exploited by 2030 and do not consider any limiting factors. For CO_2 prices, in a conservative assumption already adopted political targets in Germany are linearly extrapolated, which corresponding to a CO_2 price of 70 €/t for all 2030 scenarios. Additionally, we implement overall CO_2 budgets for each year as stated in the recent climate law of the German federal government (Subsection 5.1.1) with a budget of 98 Mt CO_2 in 2030. Furthermore, for 2030 we include three currently planned and already partly built high voltage direct current (HVDC)-transmission lines (Bundesnetzagentur 2020c, 2020a, 2020b). Theses grid interconnections are build from Lower Saxony (NI) to North Rhine Westphalia (NW), from Schleswig-Holstein (SH) to Baden-Wurttemberg (BW), and from Saxony Anhalt (ST) to Bavaria (BY) with a capacity of 2 GW, 4 GW, and 2 GW, respectively.

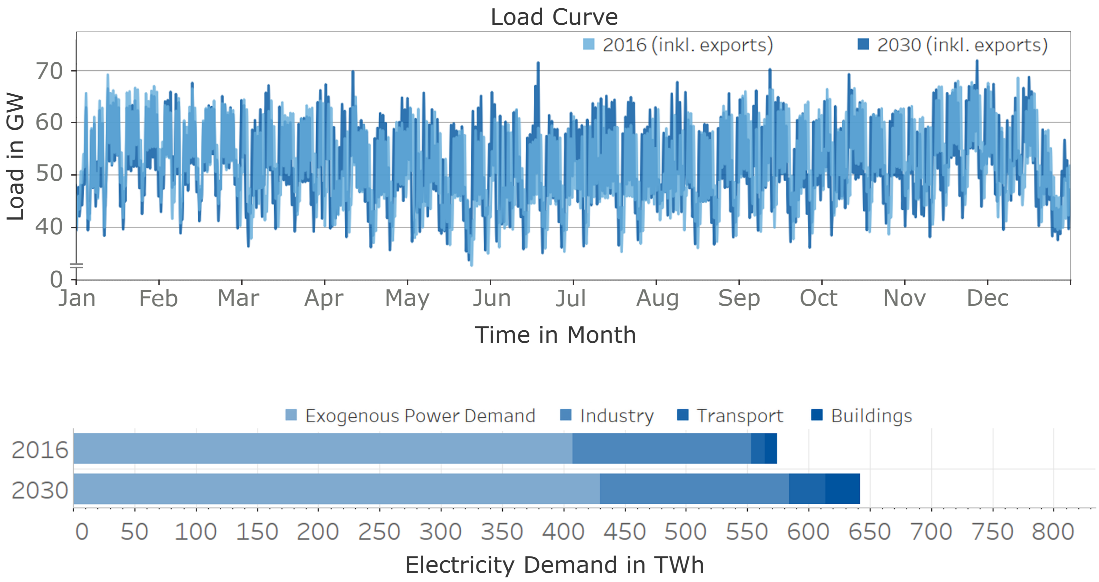


Figure 5.2: Input assumptions on electricity demand data. The top side depicts the load curve, whereas the bottom half displays the electricity demands per sector. Load curve data is taken from Löffler, Burandt, and Hainsch (2021), while sector-specific demands are taken as a result from GENeSYS-MOD computations for Germany (Löffler et al. 2022).

Furthermore, the politically set phase-out plans for power plants are included in the modeling. On the one hand, as nuclear power plants are phased-out until 2022, no capacities are remaining in all 2030 scenarios. On the other hand, the coal exit plan, as decided by the coal commission appointed for this purpose, is also implemented in the scenarios (BMWi 2019). For all other power plants, the same brownfield generation capacities as in 2016 (Figure 5.1a) are pre-installed with the option of expanding the capacities to a defined upper limit. Concerning the inner-yearly temporal resolution, electricity demand and renewable time series are provided in an hourly resolution. All models are capable to model the required degree of detail, except for *GENeSYS-MOD* that used a time-series aggregation algorithm based on Gerbaulet et al. (2019). The hourly granularity of time series used for this model comparison exclusively allows for the analysis of aggregated energy flows and is not detailed enough to analyse stability issues within the power system, that may arise from high shares of VRE generation capacities.

The scenario set-up of all eight scenarios and corresponding assumptions and parameters is summarized in Figure 5.3. With the base set-up in Figure 5.1 we define two base scenarios for the years 2016 and 2030 (Base 2016 and Base 2030). They serve as a basis for a fundamental model comparison. The base scenario for 2030 is then further used to derive five sensitivity scenarios which include variations of single policy relevant parameters and characteristics. In a final scenario referred to as "Policy 2030", variations III to V are combined to replicate the most relevant policy targets by the new German coalition, that was elected in December 2021. However, this scenario is not intended to compete with the most accurate modeling existing in literature, since simplifications of our models in terms of the harmonization process are inevitable. Simplifications include inflexible demands for sector coupling as well as inflexible imports and exports to neighboring countries. The main purpose of the "Policy 2030" scenario is to identify general trends that result from updated policy targets.

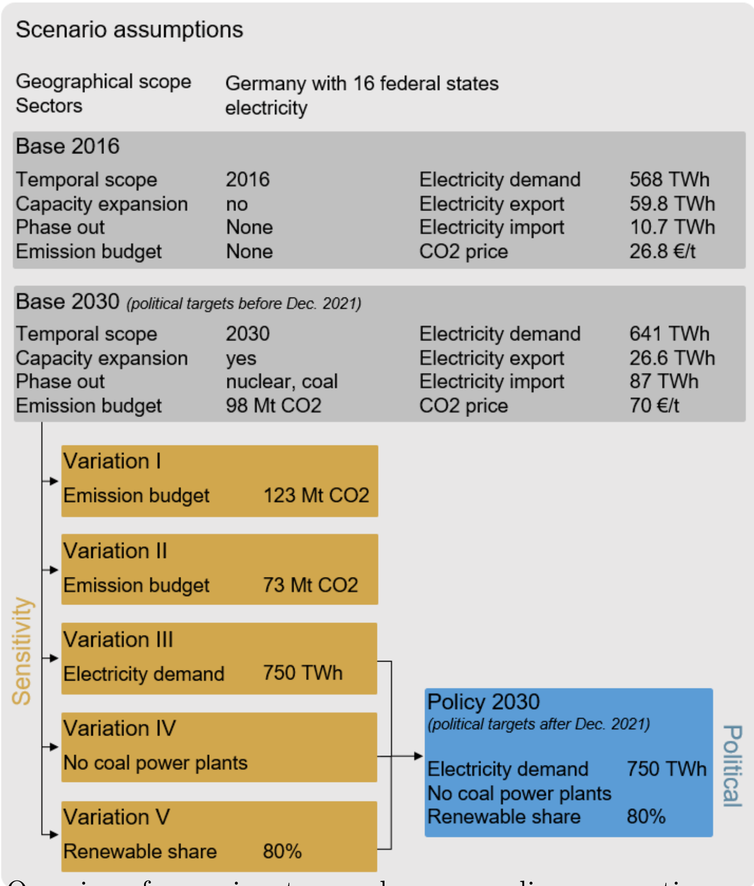


Figure 5.3: Overview of scenario set-up and corresponding assumption, as well as important characteristics.

5.2.2 Contributing power system models

With *Balmorel*, *Genetic Optimisation of a European Energy Supply System (GENESYS-2)*, *GENeSYS-MOD*, *oemof*, and *urbs*, five OSPSM contribute to this model comparison. Each of these models in turn represents only one possible configuration of its underlying and eponymous OS energy system modeling framework. All contributing models can be characterized as Open Source, techno-economic optimization models that are mainly applied for capacity expansion planning and dispatch optimization. An overview of a criteria-based methodological comparison is presented in Table 5.3. The contributing models are developed in one of the main programming languages GAMS, Python, or C++ and published under an OS license. All of the five models are based on a bottom-up analytical approach. However, in contrast to all other linear program (LP)-based models, the *GENESYS-2*-model uses a rule-based dispatch algorithm and heuristics to define and solve the optimization problem. For this reason, it can also be used as a simulation tool and is particularly suitable for the analysis and optimization of long-duration seasonal storage. Although the remaining LP-based models have a very similar basic approach, each model has its own special features. *Balmorel* for instance features add-ons for enabling couplings between the power, district heating, gas, and hydrogen sector. Furthermore, it also has the ability to include social welfare maximization in the objective function. The *Global Energy System Model (GENeSYS-MOD)* is mostly used for long-term energy system scenarios at various regional levels. Furthermore, it provides a number of demand time series models and has integrated time series aggregation functionalities. The *Open Energy Modelling Framework (oemof)* and *urbs* show the greatest variability in frequently used or existing approaches related to *temporal scope*, *regional scope* and *grid model*. Furthermore, *oemof* and *urbs* provide linear optimal power flow (LOPF) functionalities. In contrast to *GENESYS-2* and *GENeSYS-MOD*, *Balmorel*, *oemof*, and *urbs* also allow for mixed-integer linear programm (MILP).

Table 5.3: Overview of contributing models.

	Balmorel	***GENESYS-2***	***GENeSYS-MOD***	***oemof***	***urbs***
Classification	Open Source, techno-economic optimization models for capacity planning and dispatch optimization				
Programming language	GAMS	C++	GAMS	Python (Pyomo)	Python (Pyomo)
Licence	ISC	LGPL	APL 2.0	MIT	GPLv3.0
Documentation	The Balmorel Open Source Project (2022) and Wiese, Bramstoft, et al. (2018)	Bußar (2019) and Siemonsmeier, Bracht, and Bußar (2018)	GENeSYS-MOD contributors (2022)	oemof developer group (2022)	Dorfner (2021)
Analytical approach	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up
Mathematical approach	(MI)LP	rule-based dispatch, heuristics	LP	(MI)LP	(MI)LP
Temporal scope (mainly used)	short term, mid term, long term	long term	long term	short term, long term	short term, mid term, long term
Variable time steps	++	–	++	++	++
Regional scope (mainly used)	local, regional, national, multinational	local, regional, national, multinational	regional, national, multinational	local, regional, national, multinational	single projects, local, regional, national, multinational
Grid model	Single-node, Transshipment	Single-node, Transshipment	Single-node, Transshipment	Single-node, Transshipment, LOPF	Single-node, Transshipment, LOPF

Table 5.4 depicts an overview of individual modeling choices, which are model specific and not predefined in the scenario input data set. Two types of storage are distinguished: *short duration-storage* (referenced as ”short”) and *long-duration storage* (referenced as ”long”). Under short-duration storage we include batteries and pumped hydro storage whose energy-to-power (E2P) ratio (E2P ratio (short)) has been fixed in all models. On the contrary, we classify hydrogen cavern storage as long-duration storage whose E2P ratio (long) is fixed for *Balmorel*, *GENeSYS-MOD*, and *urbs*, yet it is optimized in *GENESYS-2* and *oemof*. The ratio of rated charge-to-discharge (C2D) power can either have a fixed ratio or is part of

the optimization. For short-duration storage the C2D power ratio of all models is fixed and equals 1. For long-duration storage, this also applies, except for *GENESYS-2* and *oemof* in which the C2D ratio is optimized. The model configurations also differ with respect to the state of charge in the first time step (initial storage level), which is either set to 0 or is an optimization variable. The state of charge in the last time step of the optimization (final storage level) is either set equal to the initial storage level or optimized, depending on the model. Looking at transmission, all models apply the *transshipment model* (Medjroubi et al. 2017) in which the grid is represented by multiple nodes that can exchange power. For each node an upper threshold limits the usable net transfer capacity, hence no physical characteristics of power flows are considered. The numbers of lines between nodes, however, is not equal between contributing models. Whereas in all LP-based models a back and forth connection between two nodes is modeled, in GENESYS-2 only unidirectional flow via one line is possible. Furthermore, differences occur in terms of the investment model applied and the implementation of VRE-shares is only an available feature in some of the contributing models.

Table 5.4: Individual modeling choices, which are model specific and not predefined in the scenario input data set. They are a result of the modeling process and do not necessarily represent the full capability of the models.

	Balmorel	***GENESYS-2***	***GENeSYS-MOD***	***oemof***	***urbs***
Storage					
E2P ratio (short)	fixed	optimized	fixed	fixed	fixed
E2P ratio (long)	fixed	optimized	fixed	optimized	fixed
C2D power ratio (short)	1	1	1	1	1
C2D power ratio (long)	1	optimized	1	optimized	1
initial storage level	optimized	0	0	0	optimized
final storage level	fixed to initial	optimized	fixed to initial	fixed to initial	fixed to initial
Transmission					
grid model	Transshipment	Transshipment	Transshipment	Transshipment	Transshipment
lines between nodes	2	1	2	2	2
Other					
investment model	annuity	annuity	per-period capital investment	annuity	annuity
VRE share	not implemented	not implemented	capacity limit	capacity limit	not implemented

5.2.3 Model and data harmonization

A comprehensive model comparison requires sufficient harmonization of the model configuration and the input data. Above all, it is essential to harmonize the definition of total system costs as the contributing models partly feature different interpretations of cost calculations (Candas et al. 2022a). This needs to be considered in the model-specific interface (connector) to the input database. To avoid misinterpretations, the definition of total system costs in (5.1) is used throughout this model comparison. Total system costs (TSC), also referred to as objective value, consist of investment costs (IC), fixed costs (FC), and variable costs (VC). For investment costs, we exclusively consider expanded capacities while existing capacities are considered depreciated. On the contrary, fixed costs are included as a technology-specific percentage of all existing and expanded capacities. The operational expenditures are represented by variable costs that consist of fuel costs and CO_2 emission costs. It is important to note that costs for unintended load shedding (unsupplied load) are not displayed in the definition of total system costs. They are nevertheless part of the objective value that is minimized in all models. We harmonize costs for unsupplied load and ensure feasibility of all models by modeling a slack variable that can only generate electricity with very high variable costs. On the contrary, possible surplus from VRE sources is defined as curtailment.

$$TSC = IC + FC + VC \tag{5.1}$$

The input data harmonization process follows a formalized procedure. All participating OSPSM follow this procedure to ensure input data harmonization across all OSPSM and thus model comparability (Figure 5.4). The data harmonization is intended to achieve a uniform and partially automated parameterization of the models. The procedure aims to avoid errors when transferring technology data into the models and changing scenario data through central data curation and partially automated deployment. Additionally, it leads to time savings, especially with many scenario runs.

The input scenario data is stored and maintained in a database on the OEP by utilizing a subtype of the Open Energy Datamodel (oedatamodel) format that is referred to as oedatamodel-*normalization* format. The oedatamodel (Open Energy Family 2021) was specifically designed for the comparison of energy system models that examine scenarios with a high level of detail. It consists of three tables to distinguish between scenario-specific data (scenario table), scalars data (scalars table) and time series data (time series table). The scenario table holds basic information like name, year, and region, among others, of the scenario and works as a reference to related scalar and time series entries. Both the scalars and time series table hold the techno-economic data of the scenario and technologies. Data is deployed to models through so-called *connector*s, which convert data from the efficient oedatamodel-*normalization* database format to the more user-friendly oedatamodel-*concrete* tabular format or other model-specific input data formats. The data management procedure is depicted in Figure 5.4. Customized tabular input data can be downloaded directly from the OEP via the oedatamodel API as either CSV or JSON-files. After model parameterization and optimization, the results from each model require a backward conversion. Therefore, model-specific output *connector*s linked to the oedatamodel application programming interface (API) convert model output data back to the oedatamodel-normalization format, which is then equally structured as the input data format. Thus, output data of all models can be easily fed back into the OEP database and compared with a connected dashboard (Reiner Lemoine Institut 2021).

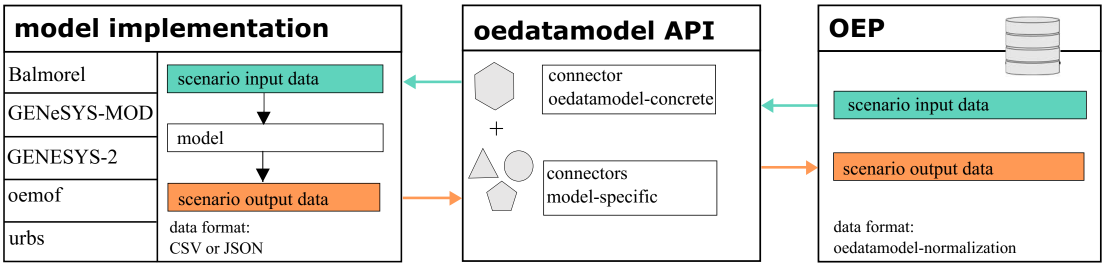


Figure 5.4: Data management workflow for the model comparison with five OS models.

5.3 Result comparison and analysis

5.3.1 Base scenario results

Applying harmonized scenarios in a model comparison helps to understand fundamental correlations between model differences and result variations. Therefore, we compare the base scenario results for the years the 2016 and 2030 of all contributing models. One of the most important indicators of result differences is total system costs (definition in (5.1)) which are minimized in all models. Figure 5.5 illustrates the model-specific results for total system costs, which in turn consist of fixed, investment, and variable costs. The results highlight that in 2016 all models reach a very similar cost level, *GENESYS-2* being the only exception showing about 40% higher costs accumulating to almost 35 billion euros. The difference in *GENESYS-2* is mainly driven by increased variable costs. The pre-defined dispatch order in *GENESYS-2* eliminates foresight and reduces the flexibility of generating, storing, and transmitting energy. In addition, the structure favors the local use of energy and limits transmission via grid into more distant regions. These limitations lead to a less cost-effective use of technologies in *GENESYS-2* and increased overall system costs in comparison with the other LP-models that find a more optimal dispatch.

For 2030, the variable costs for all models decrease in comparison with 2016, since the implementation of a GHG-reduction target coupled with a CO_2 price lead to an expansion of VRE generation capacities that are characterized by low variable expenditures. On the flip side, this adds a large share of investment costs due to increased generation capacities and causes a slight increase in fixed costs in all models. However, in *GENESYS-2* those effects are less pronounced which indicates that thermal power plants are still used to a great extent. This is supported by the slightly higher variable expenditures in comparison with the other models. Similar investment costs for *Balmorel*, *GENeSYS-MOD*, *oemof*, and *urbs* indicate that they derive at similar optimal system configurations. Nevertheless, it can be observed that small differences occur between the remaining models. They are most likely caused by different investment decisions into flexibility technologies like storage and transmission capacities. Overall, the results in 2030 highlight that with a substantial different approach, like the dispatch hierarchy in *GENESYS-2*, OSPSM can derive at very different optimal solutions.

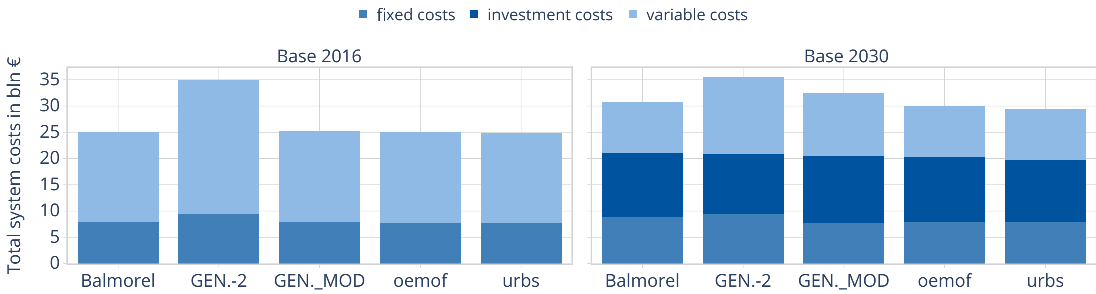


Figure 5.5: Total system costs for base scenarios 2016 and 2030, for all contributing models.

To further understand the observed differences in total system costs, we compare the results for the optimal generation (dispatch) calculated by all contributing models (Figure 5.6). The reference value (REFERENCE) displays the historical values for the year 2016 from BMWI (2019a). The results show that the dispatch for all models, besides *GENESYS-2*, is almost identical. Around two-thirds of total electricity is generated by lignite and hard coal-fired power plants (about 58%), followed by nuclear power plants (about 14%), wind power plants (about 10%), and solar PV (about 7%). Oil, gas, hydro, biogas, and biomass power plants only contribute shares of 3% or below. This solution represents sort of an optimal dispatch of the power system that could be reached if it was operated in the most cost efficient way possible, with perfect foresight considered. However, the comparison with historical net generation values (REFERENCE) reveals that the dispatch of the actual power system looks considerably different. Above all, generation from gas-fired power plants and oil power plants is more pronounced in comparison with the LP-model results. This more diverse technology portfolio is a consequence of market mechanisms and structure, that determine the actual allocation of generation capacities. This also proves, that the real-world system is usually not operated in the most cost-effective and efficient way. In the contributing LP-models, however, a market structure is not implemented, and therefore, technologies with lower marginal cost, like lignite-fired power plants, are used more extensively across the system. On the contrary to the LP-models, the dispatch obtained in *GENESYS-2* almost entirely follows the dispatch displayed by the historical values. This is caused by the dispatch order in *GENESYS-2*, that sets a fixed rule-based hierarchy including a merit order list for generation plants on a local scale and thus can better reflect the historic German market behavior of 2016, within the boundaries of this specific scenario set-up. Cheap, large, and centralized power plant units like lignite power plants are used less, while distributed, small, and more expensive power units like gas power plants are used more often (see Figure 5.6). This effect is also amplified by the GENESYS-2 structure considering local generation before importing from other regions, which leads to less lignite generation that is concentrated in very few regions in Germany. Generally, this proves that models with rule based dispatch structures can be very useful tools to provide accurate results for today's power system and can be a trade-off between an optimal and plausible solution. However, the digitization of the power system is a paradigm shift that might lead to different future market structures that will most likely require dispatch-based models to adapt.

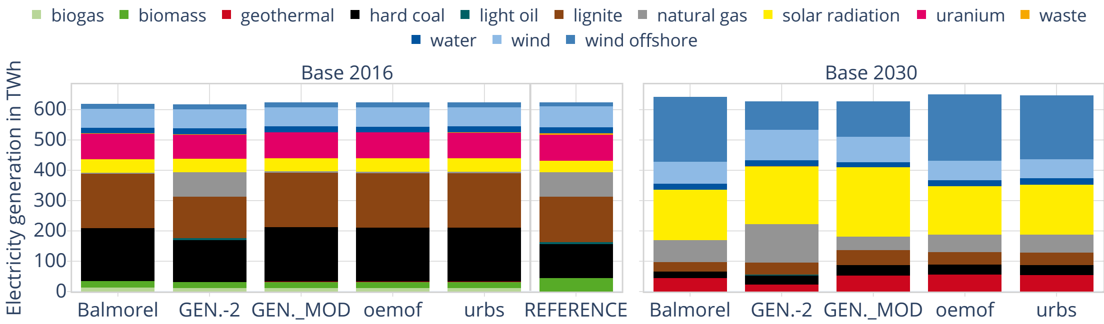


Figure 5.6: Optimal dispatch for all power plants considered in base scenarios 2016 and 2030, for all contributing models.

For 2030, results indicate that total generation only increases by small margins compared to 2016, despite the clearly increased demand from 568 TWh to 641 TWh. This is caused by a shift from exports towards imports. While in 2016 the export-import balance to neighboring European countries was positive with about 49 TWh of exports, the assumption for 2030 is a balance shift towards imports with a balance of about -60 TWh as shown in Figure 5.3. Furthermore, the optimal dispatch of all contributing models reveals a substantial shift towards renewable generation, with renewable shares ranging from 67.8% in *GENESYS-2* to 80.5% in *Balmorel*. Moreover, the dispatch results for *oemof* and *urbs* are almost identical. This is expected, since both models feature a very similar approach (Candas et al. 2022a), and proves the reliability these models are able to provide. Nevertheless, small differences, like increased generation from wind offshore and decreased generation from solar PV in *oemof* compared to *urbs*, also occur. This is partly caused by different levels of technology modeling detail and divergent modeling choices (Table 5.4). Considering the other models, the dispatch results of *Balmorel* are closest to *oemof* and *urbs*. However, in *Balmorel* slightly higher shares of distributed solar PV and onshore wind are found in the optimal solution together with slightly more electricity being transmitted. A similar, but more pronounced effect can be seen in the *GENeSYS-MOD* dispatch, that shows about 40% higher generation from solar PV in comparison with *oemof* and *urbs*. *GENeSYS-MOD* favors a system based on solar PV and short-duration storage like batteries. One major difference between *GENeSYS-MOD* and the other models is the way of how investment costs are being accounted for, since for the former all costs occur in the year where the capacities are built (and are subsequently "refunded" at the end of the modeling period) while the other models use an annuity calculation for their capital expenditures. As a result, *GENeSYS-MOD* favors a solution with less variable and more investment costs which in this case consists of a system composed of solar PV and storage. In contrast to all other models, the dispatch results in *GENESYS-2* show a higher share of fossil fuel-based thermal power plants, with a strong tendency towards gas-fired power plants. Since the dispatch model reduces flexibility, renewable generation cannot be utilized and distributed as effectively as in LP-based models. Therefore, gaps in supply are preferably covered by flexible thermal power plants.

Apart from minimizing total system costs one of the other major policy requirements is to accurately model or determine CO_2 reduction targets. For all models, the CO_2 emission results for the 2016 base scenario are clearly below the reference value (REFERENCE) of 327 megaton (Mt), (BMWI 2020) (Figure 5.7). This might be caused by inefficient fuel usage in real world generation units due to part load behaviour, among others, or by different accounting methods of emissions from CHP plants. Between all models, except for *GENESYS-2*, there are only small differences for 2016 emissions, as the dispatch obtained for fossil fuel thermal power plants in *Balmorel*, *oemof*, *GENeSYS-MOD*, and *urbs* is almost identical (Figure 5.6). In *GENESYS-2*, however, the pre-defined dispatch order forces increased generation from gas-fired power plants, that mainly substitutes generation from lignite- or hard coal-fired power plants. Therefore, overall emissions in *GENESYS-2* are lower than in all other models (see Figure 5.6), caused by lower specific emissions from gas-fired power plants, in comparison with lignite- and hard coal-fired power plants.

The 2030 emission results highlight that almost all models find an optimal solution substantially below the permitted CO_2 emission budget of 98 Mt implemented in this scenario. This means that investing in new VRE-capacities is more beneficial than using existing fossil fuel thermal power plant capacities, with the considered assumptions for techno-economic parameters and CO_2 prices. Furthermore, the variations between all LP-based models are only minor and range from 70 Mt in *Balmorel* to 74 Mt in *GENeSYS-MOD*. The only clear result outlier is *GENESYS-2*, that fully exploits the implemented budget, with a high share of gas-fired generation (Figure 5.7). However, the dispatch for 2016 (Figure 5.6) has shown, that dispatch models like *GENESYS-2* can be closer to the actual system operation. There-

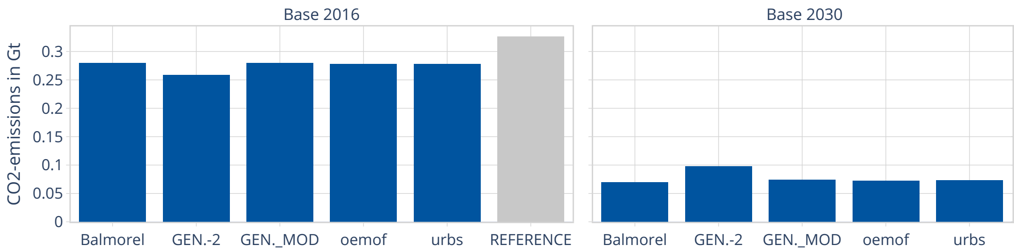


Figure 5.7: CO_2 emissions for base scenarios 2016 and 2030, for all contributing models.

fore, it is possible in LP-based models to underestimate the true emission compared to a real world system, considering that market structures in 2030 are still similar to today's.

To further evaluate and strengthen the findings, we compare all base scenario results of contributing models for existing and added capacities of generation, storage, and transmission units (Figure 5.8). In 2016, no capacity expansion for generation, storage, and transmission is allowed, thus all reported capacities are identical between the models. On the one hand, the 2016 results act as proof that all model maintainers have modeled the scenarios correctly. On the other hand, they act as a benchmark to clarify the differences. When focusing on the expanded generation capacities for 2030, we primarily notice the high expansion of solar PV in all contributing models. The highest capacity expansion for solar PV with 180 GW is detected in the capacity portfolio of *GENeSYS-MOD*, which also shows the highest generation from solar PV (Figure 5.6). For wind generation capacity expansion, a very diverse picture occurs between the models. While *Balmorel*, *oemof*, and *urbs* only invest into wind offshore, with similar values ranging between 39 GW and 42 GW, *GENESYS-2* and *GENeSYS-MOD* expand less capacity in total, but have a share of wind onshore. This is mainly caused by different grid representations that substantially influence distribution of generation from offshore wind. For *Balmorel*, *oemof*, and *urbs*, it is beneficial to strongly invest in grid infrastructure to distribute high generation shares from offshore wind from the north to the south. For *GENESYS-2* high investments into grid infrastructure can be seen as well, however, due to the dispatch model, energy can be distributed less efficiently, and local generation is preferred. In *GENeSYS-MOD* fewer investments into grid infrastructure are reported, since, as discussed above, local solar PV generation coupled with batteries is preferred over wind capacities and hydrogen cavern storage. On the contrary, *GENeSYS-MOD* builds higher capacities of storage to store generation from solar PV. Due to the fixed E2P ratios for both short- and long-duration storage, mainly battery storage is built (Table 5.4). Apart from *GENeSYS-MOD*, only *oemof* reports noticeable investments in storage capacities. It mainly invests into long-duration hydrogen storage as in contrast to the other models the E2P ratio is considered flexible for this technology and can be optimized. This makes them more suitable than battery storage to store large amounts of energy for a longer period.

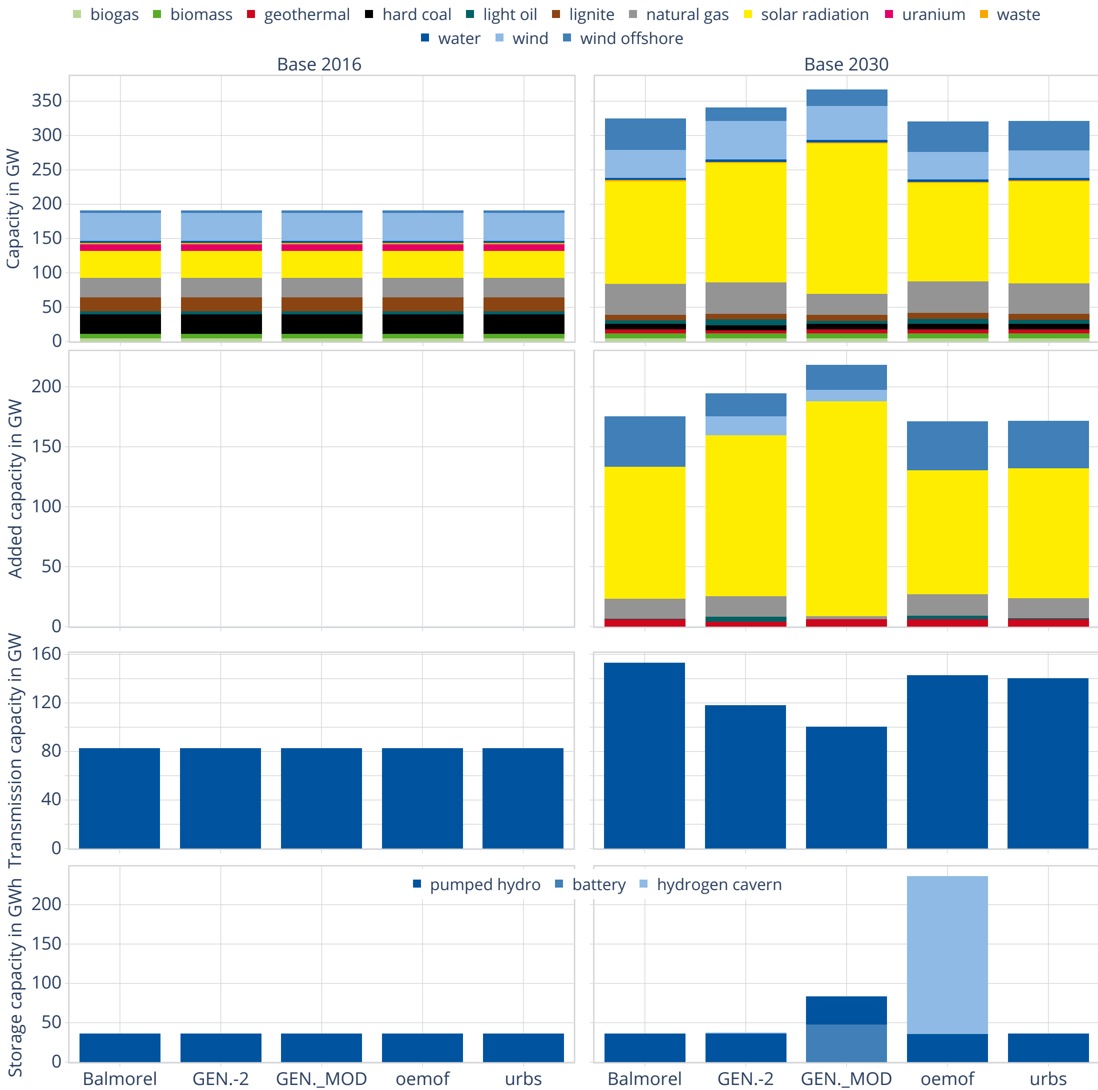


Figure 5.8: Capacity and added capacity for all power plant, storage, and transmission technologies included in the 2016 and 2030 base scenarios, for all contributing models.

More insights into model differences can be gained from different investment behavior regarding thermal power plants. In *GENeSYS-MOD* fewer investments can be obtained, whereas all other models invest substantially into new gas-fired power plants. Since gas-fired power plants have comparably high variable costs, the earlier mentioned preference for investment costs lead to only few new plants being built in *GENeSYS-MOD*. For *GENESYS-*

2, the dispatch structure favors local use of energy. Therefore, geothermal generation is only expanded by small margins and few local light oil based power plants are build to cover peak loads. The other models, however, almost fully exploit the available geothermal potential of 6.4 GW, since they can flexibly use its generation across the grid. Moreover, with geothermal power plants, it is at the same time possible to reduce emissions without loosing flexibility in generation. Moreover, geothermal power plants are also clearly preferred before zero-emission biomass and biogas power plants, resulting from lower marginal operation costs.

A holistic consideration of all interactions in the base scenario requires to investigate the use of flexibility technologies. Figure 5.9 shows the curtailed energy from VRE generation, the uncovered load (slack), the storage discharge, and the transmitted energy, for base scenarios 2016 and 2030, as well as for all contributing models. The results indicate that overall the curtailed energy increases from 2016 to 2030. As renewable generation capacity expands largely in 2030 (Figure 5.8), the surplus of VRE generation increases simultaneously. With increasing surplus, it becomes less economical to store or transmit the energy, such that curtailment remains as the last option for the models to ensure a feasible energy balance. Between the models, there are significant deviations in curtailed energy. For 2016, *GENESYS-2* reports a higher value compared to all other models, which proves that the implemented dispatch hierarchy effectively reduces the flexibility to make use of VRE generation. On the contrary, in 2030, the lowest value for curtailment is shown in *GENeSYS-MOD*. The reason can be found in the storage discharge results. Of all models, *GENeSYS-MOD* has the highest storage throughput with 23 TWh (mainly battery storage), of which a high share can be allocated to shifting its high solar PV generation (Figure 5.6) in time. In *oemof* a slightly lower storage throughput of 17 TWh that mainly comes from hydrogen cavern storage is reported. In comparison with *urbs*, that utilized less storage and transmission, *oemof* is less efficient in energy distribution and therefore has slightly higher total system costs (Figure 5.5), despite a very similar dispatch (Figure 5.6). Small differences in individual modeling choices like inflexible storage levels in *oemof* (Table 5.4) are a potential reason for this behaviour. For *Balmorel*, transmitted energy is even higher than in *oemof* as it has the highest share of generation from VRE of all models, which needs to be distributed across regions. In contrast to all other models, *GENESYS-2* avoids grid transmissions as much as possible. This is especially pronounced in 2016 when all other models have similar values for transmitted energy, but *GENESYS-2* is only reporting about 20% of this amount.

The occurrence of uncovered load is only possible in 2016 since no capacity expansion is allowed. In 2030, the existing electricity capacity generation would consistently be increased to meet the demand, since uncovered load is penalized with high costs. The results show

Figure 5.9: Usage of model flexibility technologies separated into curtailed energy from VRE, storage discharge, and transmission usage, for base scenarios 2016 and 2030.

small values (of less than 0.1% of total demand) of uncovered load in 2016 for all models. This is a result of the scenario set-up as all of the uncovered load occurs in the federal state of Saarland (SL). The geographical overview in Figure 5.1 highlights that only one transmission connection from SL to other states is modeled, since it is located at the outer German border. Additionally, imports from neighboring European countries are modeled as fixed time series. However, both assumptions are based on different sources. Therefore, the combination of location and reduced flexibility of the transmission imports is the main driver for increased uncovered load. This also shows that simplifications in modeling, that result from different sources, should be used carefully to avoid such unwanted effects.

5.3.2 Influence of key modeling parameters

The identified effects in the base scenarios analysis have to be further validated on a broader data foundation. Therefore, to strengthen the model comparison, we perform scenario variations with selected, politically relevant parameters of the base scenario for 2030. Key parameters include the CO_2 emission budget, the sum of total demand, generation capacity restrictions, and the renewable share. With this selection, it is possible to analyze the effects of different model approaches and technology modeling and to evaluate the impacts of single political measures on overall model results.

For the first two scenario variations, the emission budget of the base scenarios (98 Mt) is increased by 25 Mt (to 123 Mt) in Variation I and lowered by 25 Mt (to 73 Mt) in Variation II. Those variations are sensitivities chosen exclusively for this model experiment, and do not reflect any political targets. Figure 5.10 shows the deviations for generation, costs, and emissions, compared with the results of the 2030 base scenario. While all LP-based models show the same results for all variations of the emission budget, the optimal solution in *GENESYS-2* highly depends on that parameter. For all variations, *GENESYS-2* fully exploits the emission budget. Therefore, a higher budget of 123 Mt in Variation I leads to increased generation from fossil fuel-based power plants, especially for gas-fired technologies. Moreover, with decreasing emission budget, costs increase in *GENESYS-2*. This concludes that investments into VRE generation capacities are generally less economically viable for the range of the considered emission budget. For all the other models, solutions below the 78 Mt threshold are optimal so that a change of the emission budget does not affect results.

For future scenarios in energy system modeling, the total electricity demand is variable that has a high uncertainty. With the emergence of sector coupling applications, the demand for 2030 can only be an estimate. Therefore, in Variation III, we increase total electricity demand from 641 TWh in the Base scenario 2030 to 750 TWh, which is in line with the estimates of the new German government (SPD, Bündnis 90 / Die Grünen, and FDP 2021). For all models, higher demand results in increased emissions and costs, which is an expected pattern (Figure 5.10). However, the amount of generation and the correlation between the models changes compared to the *Base 2030* scenario. In *urbs*, the generation and costs increase to a greater extend than in all other LP-based models. This shows that in *urbs* it becomes increasingly expensive to distribute energy generation with higher generation shares from VRE. The same, but less pronounced effect is illustrated by increased generation of *GENESYS-2* compared to *GENeSYS-MOD*. The underlying dispatch model of *GENESYS-2* is less efficient than LP-based models and therefore higher generation is required.

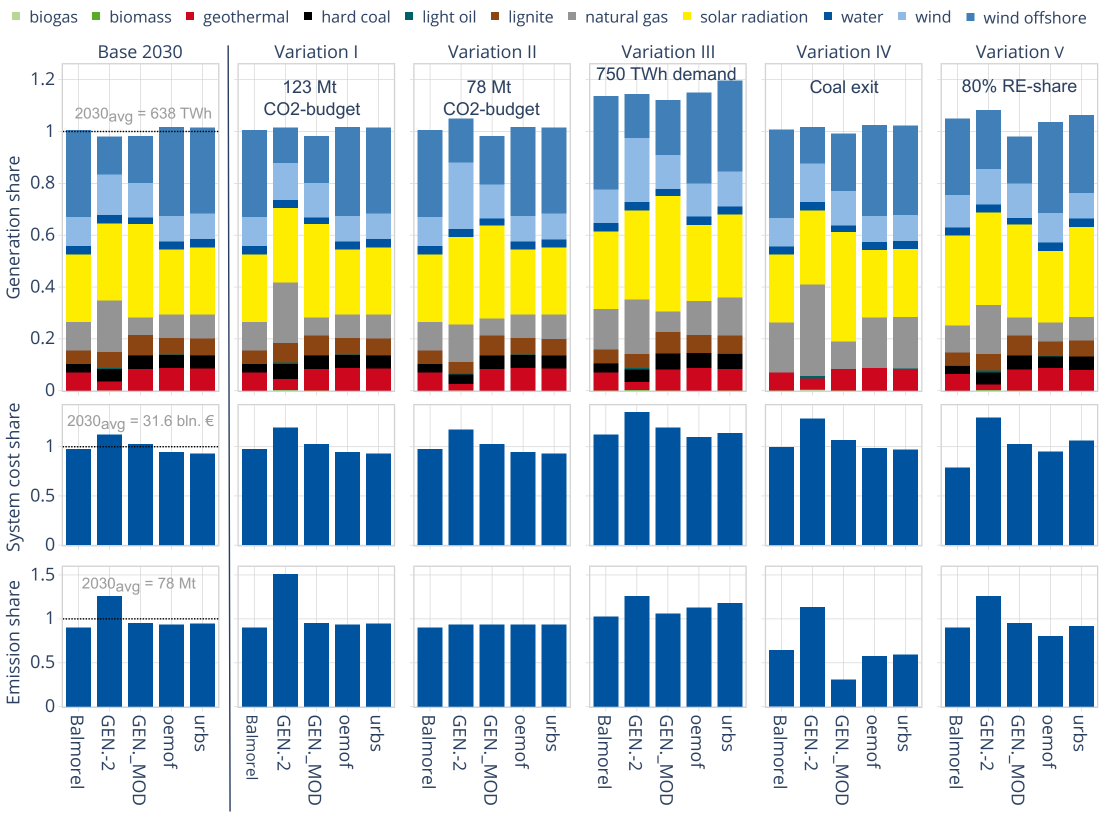


Figure 5.10: Variation of generation, costs, and emission results for sensitivities of key modeling and policy parameters, normalized to the average of the base scenario results of 2030.

One key topic that has shaped the energy transition debate in Germany is the coal exit (see Section 5.1.1). Therefore, Variation IV does not allow for any generation from lignite- or hard coal-fired power plants. One general effect illustrated by the results is that the generation pattern between the models, except for *GENESYS-2*, stays rather constant

(Figure 5.10). This indicates that without generation from coal power plants, the system does not entirely change. Instead, the generation gets mainly substituted by generation from gas-fired power plants. Consequently, the overall system costs increase slightly, but emissions are substantially reduced. In *GENESYS-2* the shift towards gas is even more pronounced as it makes higher use of the CO_2 budget. Nevertheless, in comparison with the *Base 2030* scenario, it does not fully exploit the budget. Despite this, the renewable share in *GENESYS-2* drops to a minimum of 67,3%. The coal exit thus does not guarantee that the 80% renewable target is met. It nevertheless effectively reduces emissions by 12 Mt (*GENESYS-2*) to 50 Mt (*GENeSYS-MOD*), depending on the model.

Another possible parameter to set reduction targets is the renewable share in generation. The new German government that was elected in December 2021 has raised the target for this share to be at least 80% in 2030. In Variation V all capable models apply this share. However, in the versions of *GENESYS-2* and *urbs* used for in this analysis, it is not possible to model this target. Therefore, we include additional constraints for minimum capacities that have been proposed by the new policy agenda. This includes a minimum of 200 GW of solar PV, and a minimum of 30 GW of wind offshore capacity. The results of Variation V in Figure 5.10 highlight that a renewable share as implemented in *GENeSYS-MOD* and *oemof* has only minor effects in comparison with the *Base 2030* findings. While emissions are reduced by small margins for all four models, the reduction is substantially more pronounced in *oemof* and *urbs*. Nevertheless, the emission results prove that the renewable share alone is ineffective in reducing emissions and needs to be combined with other measures like the coal exit. With the results from models without ability to model a renewable share (*GENESYS-2* and *urbs*), it further is possible to evaluate if the proposed minimum VRE capacities are sufficient to reach the 80% renewable target as well. The results indicate that this might be possible as *urbs* reports a renewable share of 80,8%. However, in a less efficient system representation, like in *GENESYS-2*, this is not the case as the renewable share is only at 71.4%.

5.4 Policy implications of model comparisons

The analysis in Section 5.3.1 and 5.3.2 supports that model comparisons provide a solid basis to discuss general trends that arise in an energy transition process. This is why the insights can also be valuable for the political debate. The variety of approaches and assumptions used by the contributing models of this comparison gives us the opportunity to analyze the new climate policy goals of the new German government from different angles. The regulation proposals by the new German coalition that was elected in December 2021 show more ambitious targets for CO_2 emission reductions compared to the status quo of the previous government. However, implications for the required transformation of the power system partly remain unclear and need to be evaluated. Therefore, we adjust the *Base 2030* set-up, that represents the targets of the previous government, with the new targets, and model it with all contributing models, respectively. The adjustments include a minimum capacity of 200 GW of solar PV and 30 GW of wind offshore, a renewable share of 80%, the exit from coal generation, and a higher annual demand by increased sector coupling (for more details refer to Section 5.1.1). Figure 5.11 shows the optimal dispatch and curtailment detected by all contributing models for the "Policy 2030" scenario. The scenario can be classified as "ambitious", as it considers the option for high investments into wind offshore and geothermal power plants. Whether it is realistic that available potentials for VRE capacities can be exploited until 2030 is not further analysed in this manuscript.

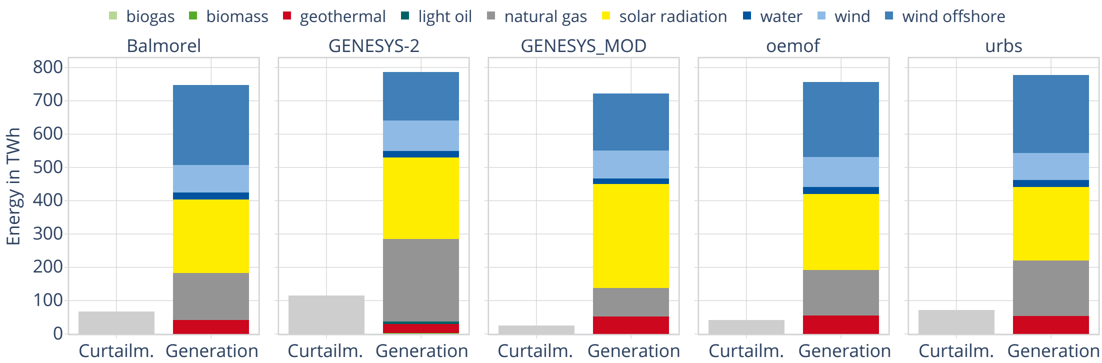


Figure 5.11: Electricity generation and curtailment of contributing models for the Policy 2030 scenario, including the proposed policy targets of the newly elected German coalition.

The optimal dispatch reveals that not all models reach the required CO_2 reductions to meet the required 80% renewable share. In the used versions of *GENESYS-2* (67.3% renewable share) and *urbs* (78.5% renewable share) the implementation of this constraint does not exist. Therefore, only minimum capacities could be applied. This implies, that the intended minimum capacities of 200 GW of solar PV and 30 GW of wind offshore of the new German coalition do not guarantee, that emission reduction targets are met. Additionally, all other models that meet the 80% renewable share propose higher shares of wind offshore, ranging from 36 GW to 54 GW. This represents ideal system configuration, and does not consider if it is realistic from an installation point of view to reach such high shares until 2030. Nevertheless, this trend clearly supports, that investments into wind offshore are beneficial and should be increased to the maximum extent possible. For models with lower shares of offshore wind, the generation is mainly substituted by wind onshore, that has lower capacity factors and therefore is not prioritized as first solution. Another important factor to notice is that the scenario set-up allows for high investments into geothermal power plants. As they provide a maximum of flexibility, their full potential of about 6.4 GW is build in all models, except for *GENESYS-2*, which applies the less flexible dispatch approach. At the same time, the generation in *GENESYS-2* is highest which also leads to the largest curtailment value of 115 TWh. For the other models, it still ranges from 25 TWh in *GENeSYS-MOD* to about 71 TWh in *urbs*. This emphasizes, that the energy system in 2030 has a very high potential to increase energy efficiency which can be achieved with flexible loads by utilizing concepts like smart charging for electric vehicles (Metz and Doetsch 2012).

In order to evaluate the measures taken by the new government, the measures of the old government as shown in the *Base 2030* results (Section 5.3.1) are taken as a benchmark. Figure 5.12 shows necessary capacity expansion rates per technology, that are necessary to reach the updated targets in compared with the old targets. The benchmark between the models is very different, so that growth rates for some technologies vary by large margins. Nevertheless, general trends can be observed that are similar across the models. Results clearly show, that substantial additional investments into solar PV are required to reach the updated targets. The values between the models range from 21% to 43%. The same applies to investments into wind power. However, depending on the configuration for the old targets, the investments are either more pronounced for wind offshore (up to 58% additional capacity), or for wind onshore (up to 28% additional capacity). Apart from generation capacities a major shift is detected for storage and transmission capacities. For storage, up to 500% of additional capacity is required, considering the rather low capacities with the old targets (Figure 5.8). For transmission, up to 15% new capacity is needed, despite the already high investments in the *Base 2030* scenario (Figure 5.8). This emphasizes, that a renewable share of 80% (or higher) represents a threshold for which substantial investments into storage and/or transmission become inevitable. For all models, the results predict no substantial further investments into biogas and biomass power plants, for the updated policy agenda under the given scenario conditions.

5.5 Summary and conclusion

In a comprehensive model comparison, we compare five OSPSM by using harmonized scenarios for the German power sector. The geographical granularity of the scenario set-up consists of the 16 federal states of Germany that are interconnected with a transmission grid. The technological scope covers all relevant technologies that are available for the power sector. We exclusively conduct single-year optimizations, to find the optimal system configuration. Two base scenarios for the years 2016 and 2030 are the foundation of a detailed model comparison. For the 2016 base scenario, the results are very similar between

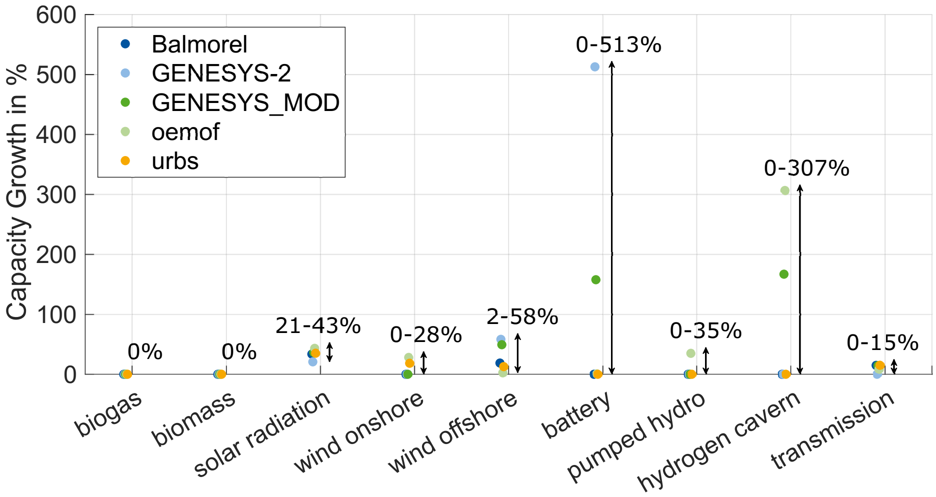


Figure 5.12: Capacity increase that is required for the new political agenda, compared to the old political targets, divided into technology groups.

models as no capacity expansion is allowed and capacities are endogenously fixed in the scenario set-up. Nevertheless, substantial differences occur between LP-based models and models with a pre-defined dispatch structure, that show about 40% higher total system costs for the base scenario 2016. The comparison of generation patterns proves, that models with a dispatch order can be closer to the real system dispatch than LP models. Reason for this is that they more accurately simulate todays market behavior, that among others relies on a merit order list for generating units. Therefore we conclude, that models with a defined dispatch order can be a trade off between the plausible and optimal solution, while LP-based models show the best possible system. However, this does not imply that one or the other is better suited, since in future systems there are higher uncertainties regarding the overall system design and efficient use of energy. Applying both approaches to future scenarios, however, can help to estimate a possible range to cover this uncertainty.

For the 2030 base scenario, the deviations between models substantially increase as capacity expansion is now allowed. With the implemented CO_2 emission budget of 98 Mt, high investments into VRE capacities are required in all models. However, this leads to very different renewable generation shares ranging from 67.8% to 80.5%. While models with a dispatch order fully exploit the emission budget and rather try to make use of existing thermal power plants, LP-based models find an optimal solution that leads to substantially less emissions as they more efficiently can distribute generation from VRE sources. Between LP-based models, variations especially occur from different use of flexibilities, like storage and transmission. For some models, it is beneficial to highly expand wind offshore capacities, as their grid representation enables them to efficiently distribute energy from North to South. In other models, investments into wind offshore are lower and the transmission grid is used less. Instead, they highly invest into solar PV capacities that are more evenly distributed across the federal states. This leads to an increased overall demand for storage and increased energy throughput. The choice of storage technology, however, turns out to be different across the models. This is mainly caused by the implementation of E2P ratios. For some models, this ratio is optimized while others consider it as fixed. The effect is especially pronounced for long-duration storage, like hydrogen cavern storage, since the investment costs for charging (electrolyzer), discharging (hydrogen gas power plants), and storage unit (salt caverns) substantially deviate. Therefore, we recommend to always optimize the E2P ratio for storage.

Since single modeling parameters and policy requirements can have a major impact on the optimal system design, we conduct a sensitivity analysis with modifications to the 2030 base scenario. The selection of modifications includes variations for CO_2 emission budgets, the total sum of demand, and the renewable share. Furthermore, a coal exit strategy is implemented. To isolate the effects the modifications are applied individually and the effect on the results are compared between all models. The variation of CO_2 budgets highlights that for LP-based models results do not change, when the optimal solution lies below the implemented threshold. While this is expected, models based on a dispatch structure tend to have a high sensitivity to this parameter as they are less efficient in energy usage and distribution. For this reason, existing fossil fuel based thermal power plants are the obvious choice before investments into new VRE generation capacities. In another variation, the total electricity demand required is increased to 750 TWh, which reflects current political assumptions for a higher sector coupling in 2030. Apart from the expected increase in costs and CO_2 emissions, the results between the models indicate that this has substantial different effects on investment decisions. This implies that the gradient of the correlation between total system costs and renewable generation share is more or less steep, depending on the model. Therefore, with higher renewable shares also the deviations between model results tend to increase.

Another topic that has shaped the energy transition debate in German is the coal exit plan. Applying a coal exit by 2030 has several effects, that are very similar across models. Despite substantially lower emissions in all models, total system costs increase with the more extensive generation from gas-fired power plants, that are characterized by high marginal costs. Thus, they mainly substitute the phased-out generation from lignite- or hard coal-fired power plants. The optimal system configuration, however, remains largely the same. Only in models with a dispatch order this leads to lower renewable shares as gas-fired power plants can be used extensively without violating existing emission budgets. In a last variation, we evaluate the effectiveness and implications coming from renewable shares as a model constraint. Our analysis proves, that the implementation of the politically agreed renewable share of 80% in 2030 does not guarantee substantial emission reductions as generation shifts from gas- to lignite and hard coal-fired power plants. Therefore, this parameter should always be implemented in combination with other CO_2 reduction measures.

In a last step, we apply all relevant policy decisions from the new German government that was elected in December 2021 and analyse the overall trends that can be observed for the optimal system configuration. One main insight is that the proposed minimum capacities of 200 GW for PV and 30 GW for wind offshore might not guarantee that a renewable share of 80% is reached. Moreover, a comparison of the new policy targets with previous targets reveals that higher investments are required for most technologies. The additional required capacity varies between models and ranges from 21% to 43% for solar PV, from 0% to 28% for wind, and 0% to 58% for wind offshore. In addition, substantially increased investments into flexibility technologies, such as storage and transmission, are necessary. The new policy decisions correlate with a higher uncertainty in energy system modeling, as deviations between models increase.

It should be emphasized, that the scenarios conducted in this study have been simplified, in order to ensure data harmonization. The main simplifications include inflexible demands and inflexible imports. The results of our comparison prove, that most models are robust in the sense that they show similar results for different scenario variations. Nevertheless, significant differences occur that pose the question of how reliable models are for answering pressing political questions. Our analysis shows that to answer specific questions, the choice of model plays a very important role. Choosing the right model, however, depends strongly on the question that is supposed to be answered. If the purpose is to find the most optimal energy system possible, LP-based models are the obvious choice. However, to capture todays market mechanisms models with pre-defined dispatch orders can be a trade-off between the optimal and plausible solution. Additional constraints in LP models are one possibility to fill the gap between those two extremes, as future system design is of high uncertainty. One example is the definition of investment costs that can lead to solar PV generally being favored over other renewable sources. The depth of technology modeling, especially for transmission, can also make a substantial difference.

The used approach for this model comparison exclusively focuses on the power sector, including the other sectors through exogenous assumptions. Modeling an integrated energy system where sector-coupling effects are endogenously accounted for would provide better insights into the inter-dependencies within the energy system. The same applies to the modeling of flexible transmission lines to neighboring countries. If considered, they could potentially increase flexibility and reduce generation and storage demand. However, especially for future scenarios this is very challenging due to the unavailability of Open Source data. A stronger collaboration and exchange of data between scientists could substantially improve future model comparisons. For the 2030 scenarios, however, we expect that despite the simplifications our results hold as still a significant amount of thermal power plants provides flexibility. Nevertheless, we propose to use this approach and adopt it to cover sector coupling technologies and other flexibility including transmission exchange and demand response among others.

Data Availability

The data template that contains all input data for the utilized scenarios is available on: https://zenodo.org/record/5854410

Chapter 6

Chances and barriers for Germany's *Energiewende*

6.1 Introduction

To combat the adverse effects of climate change, a large-scale transformation of the ways we generate and consume energy has to be undergone. These widely agreed upon measures are needed in order to limit global warming to below 2 degrees Celsius, the threshold set in the historic Paris Agreement. Germany, as the largest economy of Europe, has portrayed itself as very committed to climate issues, with the German *Energiewende* being a major factor in German politics for the last decade.[1]

However, while the existence of global warming, its adverse effects on the environment, and general measures of greenhouse gas emission reductions are widely accepted, the concrete steps on the pathway towards these goals is heavily debated, both in policy, and academia (Clack et al. 2017; Brown et al. 2018). A major part of this discussion is that of uncertainty, both with regard to possible outcomes, as well as to a multitude of factors such as future technology innovation (concerning both availability and costs), and final energy demands, but also socio-economic factors such as employment or sufficiency. While quantitative models can give meaningful insights into future developments, an actual realistic prediction of the future is impossible. As George Box Box 1976 famously put it: *"All models are wrong, but some are useful"*. It is thus the job of quantitative modeling to inform decision makers about possible outcomes and necessary steps to reach set goals, especially considering factors such as path dependencies. Only with well-informed decisions, the extremely ambitious goals to limit global warming can reasonably be achieved, since they require immediate action, focused on long-term goals instead of short-term near-future gains. To achieve this, modelers spend an extensive amount of time researching historic parameter values, and constructing future scenarios using assumptions on the development of said parameters.

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[1] *Energiewende* describes the German term for energy transition and is widely used within research, policy, and media, also outside of German-speaking countries (Jungjohann and Morris 2014). The term has been used since the 1970s and got well-known for Germanys early pushes towards renewable energies (Clean Energy Wire 2020).

One can therefore reasonably assume that model results themselves carry a large portion of uncertainty, albeit often being portrayed as singular, infallible results.

This paper aims to give valuable insights into this uncertainty by applying the method of exploratory sensitivity analysis to an application of the Global Energy System Model (GENeSYS-MOD) for the German energy system. By computing over 1500 sensitivities across 11 core parameters, the key influential factors for the German *Energiewende* can be quantified, and possible chances, such as so-called no-regret options, as well as potentials barriers (if assumptions are not met) can be distilled. While this paper presents an application specific to the German case, the general methodology and model changes can be universally applied to other regions as well. Also, with Germany being the largest economy in Europe and the fifth-largest in the world (both in terms of gross-domestic product (GDP)), the German *Energiewende* has been followed closely across the globe. Germany therefore has a great responsibility to ensure that global climate goals are met. Also, seeing as this paper also highlights the main drivers of cost-optimizing energy system models, many of the generated insights can be translated to other model applications as well.

6.1.1 Literature review

In general, the transformation of an energy system towards renewable energy sources has been analyzed in various studies for differing regional scopes. Hereby, quantitative energy system models have been used in a variety of ways to generate implications of transformation pathways for policy- and decision makers. Overall, several studies are available looking at possible transformation pathways for the global energy system (Pleßmann et al. 2014; Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Bogdanov et al. 2019; Ram et al. 2019). In this regard, the importance of swift and consequent actions, combined with long-term planning taking potential effects of sector coupling, are highlighted. Similarly, a plethora of studies are analyzing the region of Europe specifically. Primarily, the future need for renewable energies in a low carbon transformation of Europe is analyzed, with the possibility of 100% renewable power generation or a complete decarbonization of the whole energy system until 2040/2050 set as a focus for some case-studies (Capros et al. 2014; Gils et al. 2017; Hainsch et al. 2021; Auer et al. 2020). In this regard, the necessities and implications of European wide grid-extension for a low-carbon energy system transformation is being discussed frequently (Steinke, Wolfrum, and Hoffmann 2013; Child et al. 2019a). Furthermore, Gerbaulet et al. (2019) and Löffler et al. (2019) asses and discuss the problem of stranding assets in the fossil fueled power generation when moving away from conventional power generation. This stranded assets problem might lead to substantial economical loss of wealth, if not considered in long-term planning. While many studies often only analyze the power sector, Connolly, Lund, and Mathiesen (2016) and Hainsch et al. (2021) promote the importance of sector-coupling and its positive effects of the transformation of the European energy system.

Similarly, sector-coupling is also deemed an important factor for the energy transition in Germany, as especially coupling the transportation and heating sectors with the power sector results in different implications for energy system transformation pathways (Palzer and Henning 2014; Bloess 2019; Schill and Zerrahn 2020). As sector-coupling largely increases the power demand for future energy systems and often outpaces energy efficiency gains and demand reduction, large investments into renewable energy sources are necessary to comply to ambitious climate targets, as presented by Bartholdsen et al. (2019). For Germany, power generation from offshore wind farms is projected to become a crucial part of the future power system as large cost decreases are projected and offshore wind power generally has high load-factors for a variable renewable energy source (Staffell and Pfenninger 2016; Bosch, Staffell, and Hawkes 2019; Soares-Ramos et al. 2020). As such, it is able to substitute medium-load fossil fueled power plants (Pehnt, Oeser, and Swider 2008). With increasing shares of variable renewable energy sources, the importance of large-scale energy storage deployment needed for a successful energy transition in Germany is also assessed by certain case-studies (Zerrahn, Schill, and Kemfert 2018; Cebulla et al. 2018; Shirizadeh, Perrier, and Quirion 2020). Also the topic of net-zero emissions and the transition towards 100% renewables is discussed for Germany in various studies (Hansen, Mathiesen, and Skov 2019; Kobiela et al. 2020; Prognos, Öko-Institut, and Wuppertal-Institut 2020). For reaching the German climate targets, a decline of fossil fueled power generation is required, the economic, social, and ecological and implications of phasing out the existing coal-based power generation is being discussed by Heinrichs and Markewitz (2017) and Oei, Hermann, et al. (2020).

In general, the complexity of energy system models is currently rising due to the inclusion of higher temporal and regional detail, sector-coupling, and adding further techno-economic detail (Prina et al. 2020). The challenge of complexity is often handled by creating more flexible models in terms of spatial and temporal resolution (Lopion et al. 2018). However, even with the previously rising complexity, uncertainty in energy system planning is often neglected in energy system models, although it is widely accepted that uncertainty is a key issue for energy models (Paltsev 2017; Yue et al. 2018). In this regard, several methods of analysing uncertain elements in energy system planning could be used: stochastic programming, Monte-Carlo simulations, or robust programming. A further way of handling uncertainty is a systematic sensitivity analysis, as mentioned by Iyengar and Greenhouse (2009) and Ferretti, Saltelli, and Tarantola (2016). By reducing the complexity of the original problem it is possible to perform rigorous uncertainty and sensitivity analyses (Pfenninger, Hawkes, and Keirstead 2014). This allows for probing the decision space and to generate valuable insights for policy- and decision-makers about energy system transformation pathways (DeCarolis et al. 2016).

Overall, all of the previously mentioned studies tackling the German energy transition neglect the importance of uncertainty for energy system planning. Furthermore, no other research is available that investigates the barriers and opportunities for the German energy transition with a systematic sensitivity analysis. Moreover, the impact of sector coupling is often neglected in studies only assessing the power sector. In this regards, we propose the application of a systematic sensitivity analysis to evaluate possible chances and barriers for Germany's low-carbon energy transition using the multi-sectoral Global Energy System Model (GENeSYS-MOD), therefore answering the main research questions: (i) "What are the key influential factors for Germany' s *Energiewende*?" and (ii) "What implications does that have on energy policy advice?".

The remainder of the paper is structured as follows: the upcoming section gives an overview over the status quo of the German energy system. Section 6.2 will briefly describe the utilized model before introducing the methodology and chosen sensitivities. The results of the explorative sensitivity analysis are showcased in Section 6.3, and Section 6.4 presents the conclusions and recommendations.

6.1.2 Status quo of Germany's *Energiewende*

Germany's efforts to achieving climate protection and efficiency have a long-running record, as it is committed to several multilateral and unilateral goals (United Nations 1998; UNFCCC 2015b; BMUB 2016; Bundesregierung 2019a). Especially the climate protection law enacted in 2019 (*Klimaschutzgesetz*) is meant to be one of the cornerstones of climate protection ambitions, being the first instance of a law which defines sectoral climate goals with GHG reduction targets for the sectors transportation, energy, industry, buildings, agriculture, and waste. This includes the goal to reduce GHGs until 2030 by at least 55% compared to 1990 (Bundesregierung 2019a) and to reach climate neutrality by 2050 (Angela Merkel 2019). Measures to reach these targets include phasing out electricity production from coal power plants by 2035-2038 (Bundesregierung 2020c) as well as the introduction of an additional CO_2 price for the heating and transportation sectors which are not yet included in the EU Emissions Trading System (ETS) (BMU 2019).

With respect to the progress of the German energy transition (*Energiewende*), the early achievements of rapid deployment of wind and solar energy have slowed down over the last years. In the case of wind energy, between 2014 and 2017 a new annual capacity of 4609 GW could be observed on average, while the two succeeding years don't reach that number combined (Bundesverband WindEnergie e.V 2020). Solar PV on the other hand had its peak in new installations around the years 2012-2013 with a heavy dip afterwards, but the numbers are increasing again since 2017 at a steady rate (Solarbranche.de 2021). Yet, despite these developments, renewable energy sources accounted for more than 50% of the total electricity production in 2020 (Fraunhofer ISE 2021) and even though this is partially caused by the global COVID-19 pandemic and resulting demand reductions, it can be seen as an encouraging step towards a decarbonized electricity system.

As for the other sectors, the picture is less encouraging. According to the Federal Ministry for Economic Affairs and Energy (BMWI 2019b), space heating and warm water made up for almost one third of the total energy consumption in 2017, yet since 2012 the share of renewable energies for space heating application only increased by 2% with most of the energy coming from biomass (Umweltbundesamt 2020b). In the industry sector, energy consumption increased between 2008 and 2017, with no notable change of the share of renewable energies (BMWI 2019b). Lastly, the transportation sector shows increasing energy consumption since 2009 (BMWI 2019b), while at the same time emitting 22% more emissions than in 1995 (Umweltbundesamt 2020a).

Taking into account all sectors, overall GHG emissions were reduced by 34.3% between 1990 and 2019 (Bundesregierung 2020a). In the last year, 2020, emissions could even be reduced by as much as 45% according to estimates of the *Agora Energiewende* thinktank (Agora Energiewende 2020), a reduction that would mean the 2020 intermediate target of a 40% reduction compared to 1990 would be achieved. However, the authors point out that this reduction can mainly be attributed to the effects of the global pandemic on energy demand and consumption, since otherwise it would have been reasonable to assume that the climate target would have been missed.

The aforementioned developments highlight two aspects of the German energy transition: First, targets such as the one aimed at climate neutrality by 2050 still have to be transformed into binding laws and efforts have to be expanded in order to reach the defined climate targets since the current trajectory is not sufficient. Second, a high degree of uncertainty is predominant in the future development of the energy system, not only caused by disruptive events like the pandemic but also driven by technology development, regulations, and societal attitude. Therefore, in this work we aim to illustrate and highlight how changes in these projections can affect the configuration of the energy system and which no-regret options policy makers can focus on.

6.2 Materials and Methods

6.2.1 Model description

The model used for this analysis is the Global Energy System Model (GENeSYS-MOD) an open-source linear optimization model, encompassing the electricity, buildings, industry and transportation sectors of the energy system, which is an extension of the Open-Source Energy Modeling System (OSeMOSYS) (Howells et al. 2011b).[2] It was successfully applied in multiple case studies (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Löffler et al. 2019; Burandt et al. 2019; Oei, Burandt, et al. 2020; Auer et al. 2020; Hainsch et al. 2021), including possible pathways of the German energy system transformation (Bartholdsen et al. 2019). A stylized representation of the model is illustrated in Figure 6.1.

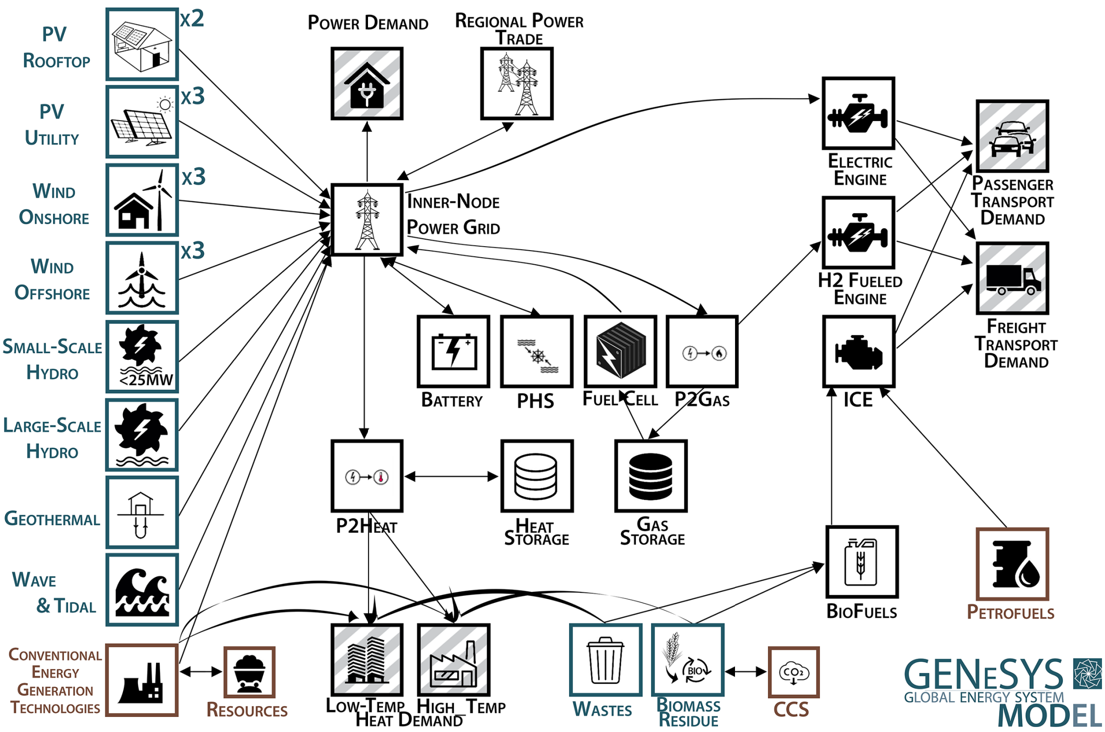

Figure 6.1: Structure of GENeSYS-MOD including its main technologies and the respective connections. Source: Own illustration.

[2]For more information and access, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public

For each time step, the model has to satisfy the exogenously defined demands for the different energy services (electricity, industry, buildings, and transportation) while also ensuring that sufficient generation capacities are provided. To achieve this, the model can choose to invest into capacity expansion of a plethora of available technologies across the sectors. This dispatch and capacity expansion optimization is carried out under perfect foresight and from a central planner perspective, meaning full information, also about future years, is available at all times. As the objective function, the model aims to minimize total system costs, encompassing both capacity expansion, energy generation, trade, storage, and conversion costs. All fiscal units are discounted towards the base year.

6.2.2 Exploring uncertainty via sensitivity analysis

The purpose of this paper is to give insights into the uncertainty that inherently comes when trying to model and quantify any aspects of the future. While the existence and general danger of global warming are widely accepted within academia and politics, the actual process and necessary degree of the low-carbon transition are still heavily debated (Clack et al. 2017; Brown et al. 2018; Schill et al. 2018). As perfect predictions of the future are impossible, the role of models should rather be to generate insights and thus useful information to improve short-term plans to be more aligned with long-term goals (e.g. in order to avoid path dependencies and/or unnecessary stranded assets (Löffler et al. 2019)).

There are various ways to tackle uncertainty in quantitative modeling, such as adding stochastic elements to the model formulation (Birge and Louveaux 2011), changing the amount of foresight applied in the model (Gerbaulet et al. 2019; Löffler et al. 2019), or modifying (uncertain) input assumptions to observe the model's behavior (Pfenninger, Hawkes, and Keirstead 2014; DeCarolis et al. 2016). This last approach is commonly known as sensitivity analysis and mostly used as a tool to validate the model workings, as it can easily point towards inconsistencies in the model results. In this study, however, a much more widespread technique is being applied - that of *exploratory sensitivity analysis*, a technique that is frequently used in various scientific fields (Iyengar and Greenhouse 2009; Ferretti, Saltelli, and Tarantola 2016).

Compared to this exploratory sensitivity analysis approach, robust or stochastic programming usually provide a singular solution instead of a range of sensitivities. Although this singular solution considers uncertainty and can be used for extensive risk assessments, robust and stochastic programming both usually result in substantially increased problem sizes, making the variation of input parameters difficult without deployment of additional decomposition techniques. Monte-Carlo simulations present a further method for analyzing uncertainty. These simulations are used to generate probabilistic results based on uncertain/random input parameters. In general, Monte-Carlo simulations are used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. However, as the input parameters are considered random variables, each model run generates a different outcome. Instead, the advantage of a large-scale (deterministic) *exploratory sensitivity analysis* as being applied in this research is the ability to always generate the same outcomes according to the changes in the input parameters. As a downside, uncertainty is not inherently included in the model setup but has to be assessed ex-post. However, due to the setup of an *exploratory sensitivity analysis*, a large variety of input parameters can be analyzed without the need for an adjusted model setup or adding artificial randomness to the variables.

As such, a wide amount of key parameters to the model are changed iteratively, yielding a total of 1591 separate sensitivities that have been considered in this study. The chosen sensitivity parameters and their value ranges are presented in Section 6.2.4. All of these sensitivity results are then cross-compared with each other, as well as with a defined reference scenario, or *base case*. We analyze each sensitivity *ceteris paribus*, thus with all other values remaining unchanged. This allows for a proper separation of effects for each sensitivity.

GENeSYS-MOD was expanded with a new module that enables this exploratory sensitivity analysis, adding the functionality to vary key input parameters via automated scripts that can then be used to run a multitude of sensitivities in parallel. In addition to the exploratory sensitivity computations, the module also introduces new automated methods for result aggregation and dissemination in GENeSYS-MOD.

6.2.3 Chosen base case scenario

To provide a reference point for the sensitivity analysis, a base case was defined and computed. Building upon the work in Bartholdsen et al. (2019), the German application of GENeSYS-MOD has been updated to the newest version of the model, including the improved time-series reduction method presented in Burandt et al. (2019).

The model depicts Germany at a federal state level, thus consisting of 16 nodes total. The years 2015 to 2050 are modeled, with 2015 being taken as a base year, and 2017 as an intermediate step between 2015 and 2020. After 2020, the model is set up in 5-year steps. This setup for modeled years has been chosen to remain comparable to the results of Bartholdsen et al. (2019) (which starts with the year 2015), while better reflecting real-world developments towards 2020 at the same time. 2017 has been chosen as an intermediate step between 2015 and 2020 since it was the most recent year where detailed data on all sectors was available. The sectors electricity, buildings, transport, and industry are included in the analysis, with a strong focus on sector-coupling options. For this analysis, no carbon budget has been implemented. Instead, the base case serves as more of a 'current policy' scenario, including a CO_2 price that has been passed as part of the "Climate Action Plan 2030" in Germany (Bundesregierung 2019b), setting the minimum CO_2 price to 55€ after 2026, expected to rise at least 85€ per ton of CO_2 in 2050. 2038 is set as an exit date for coal in the electricity sector, and nuclear power is shut down as soon as 2022. All relevant input data can be found in the accompanying supplementary material at the Zenodo repository.

6.2.4 Sensitivities analyzed in this study

In this study, a total of 1591 sensitivities, spread across 11 different parameters, have been analyzed. These parameters have carefully been selected for being part of the most influential parameters of the model, or facing the most discussion in science, media, and policy. As these sensitivities highlight the effects of changes to the base case without altering the other parameters (*ceteris paribus*), the results provide decision and policy makers with the opportunity to see how effective policies targeting a specific area would be. Therefore, the ranges of the sensitivities are not limited by what can be found in the current literature or political debate, to paint a bigger picture and possibly highlight effects which might be overlooked otherwise. With the sensitivities being computed *ceteris paribus*, no combinations of different sensitivity parameters is made in the scope of this study. Table 6.1 lists all sensitivities, as well as their value ranges.

Final energy demands

Being one of the main drivers of GENeSYS-MOD, as well as a highly uncertain factor, final energy demands are of major importance in the future development of the energy system. As their future predictions often rely on qualitative scenario assumptions, they are exposed to extreme uncertainty and heavily reliant on expert assessment. Additionally, aspects of sufficiency, which see an increased representation in recent literature (Lorek and Spangenberg 2019; Toulouse et al. 2017), are difficult to include in typical energy system modeling and usually have to be considered through exogenous assumption (such as reducing energy demands). In this study, energy demands are varied per sector, relative to the base case.

Costs of breakthrough technologies

Breakthrough technologies, especially related to hydrogen, and future energy storage concepts, are often hailed as being a cornerstone of the low-carbon transition. Especially when extremely high levels of decarbonization are targeted, many studies heavily rely on these future technologies to reduce emissions. As such, their projected costs are not only highly uncertain, but also of great importance. They are varied per technology in relation to the base case assumptions.

Growth rate of renewables

Another uncertainty is that of the maximum possible introduction of renewables into the electricity grid per year. It is often argued that there is a maximum that can reasonably be introduced without causing issues with grid stability.

Rate of transmission grid expansion

In German media and politics, there is an extensive and ongoing debate about the necessity of transmission grid expansions when incorporating more renewables into the grid. Since most renewable potentials (notably offshore wind) are located in Northern Germany, but much of the (industrial) energy demand is in the south, many argue for the expansion of these north-south transmission lines.

Renewable potentials

Even though studies show that the potential for renewable energies in Germany is much higher than required for a complete decarbonization of the energy system (F. Matthes et al. 2018), local preferences and matters of acceptance can have a major impact in the final configuration of the electricity sector. Moreover, some determinants of renewable potentials are in an ongoing discussion (e.g.: minimum distance from wind turbines to settlements) or rely on societal participation (e.g.: solar power on residential buildings). Therefore, in this case study a varying potential for onshore, offshore and solar photovoltaic simulates these uncertainties, as the exact potential for renewable energies is difficult to assess, yet the effects of increasing or decreasing said potential can be of significant importance.

Carbon price

There exists a multitude of different possible climate policies (varying from more market driven to regulatory instruments). The implementation of a carbon price for the sectors energy, industry, buildings, and transportation is hereby taken as proxy for the level of climate stringency. Yet, there are frequent differences in the magnitude of proposed carbon prices, as well as compared to already implemented ones. In this sensitivity, we significantly alter the carbon price to highlight its effects, specifically onto the different sectors. The currently agreed on carbon price trajectory for Germany consists of a price per ton of CO_2 of 25€ in 2021, increasing to 55€ per ton of CO_2 in 2025. This price corridor is already an updated version of an earlier one, which was heavily criticized as being too low, with prominent research institutes arguing for prices as high as 180€ per ton CO_2 in 2030 (Edenhofer et al. 2019b; Bach et al. 2020). Therefore, the chosen sensitivities range from 350 €/ton CO_2 in 2050 (assuming a carbon price of 180 €/ton CO_2 in 2030 with a similar development afterwards) to 20 €/ton CO_2 in 2050, assuming a decreasing development after 2025.

Building renovation rate

The building renovation rate is one of the cornerstones of reducing GHG emissions in the buildings sector, since improved insulation has a significant effect onto the energy required for space heating. In Germany, however, only about 1% of the buildings is renovated each year, far less then recommended by most studies to achieve any meaningful climate target (Kobiela et al. 2020). Therefore, in this sensitivity we analyse the effects of an increased or decreased renovation rate and the resulting effects on residential energy demand. Hence, the chosen sensitivity range assumes 1.5% as the baseline which is considered to be the minimum rate required if moderate climate targets were to be achieved (Deutsche Energie-Agentur 2019), which is then drastically altered towards both ends to simulate stagnating or very progressive policies.

Hydrogen import price

As already mentioned above, hydrogen is often viewed as a key component in the low-carbon energy transition. Apart from producing it locally from renewable energy sources, importing hydrogen would be another, yet possibly controversial, option of covering the demand. While in our base case the option for importing hydrogen is not enabled, we implement this feature in this sensitivity with the values ranging from 33.1 €/MWh to 254 €/MWh.

Modal split

The choice of vehicle to satisfy transportation demand depends on behavioural aspects and is difficult to replicate with a purely cost-minimizing approach but still can have huge implications for the energy system. Trains are generally speaking more cost and fuel efficient when it comes to produce passenger or ton kilometer, however road transportation remains (and probably will remain) the most important mode of transportation. In GENeSYS-MOD, the modal choice is very limited due to the linear nature of the model and the otherwise extreme results which would be produced. However, this sensitivity explores the potential effects of a more energy efficient modal split by allowing higher amount of transport demand being shifted towards other modes of transportation (e.g., from road-based to rail-based transportation).

Costs of renewables

With GENeSYS-MOD being a linear cost-optimization problem, costs are always one of the most influential factors. Since a large-scale introduction of renewables will be inevitable to achieve set climate goals, their costs and learning rates - being higly understimated in the past (Mohn 2020) - are highly relevant to the model results. They are varied per technology relative to the base case.

Biomass availability

Biomass usage is another often critical factor in decarbonization studies. However, one has to distinguish between actually renewable biomass (such as waste and other bi-products), and 1st generation biofuels such as fuel crops. With biomass being both a highly valuable and scarce resource (e.g. for the decarbonization of the transport or industrial sectors), its availability is an extremely important uncertainty to be analyzed.

Table 6.1: Analyzed sensitivities in this study, including quantity and value ranges for each chosen parameter.

		#	Min value	Default value	Max value	Step size
Demands	per sector	231	70%	100%	150%	2.5%
Costs of breakthrough techs	per technology	243	50%	100%	250%	2.5%
RES integration	max increase/year	131	3.5%	5%	10%	.05%
Grid expansion	max increase/year	121	0%	3%	6%	.05%
RES potentials	per technology	264	70%	100%	150%	2.5%
Carbon price	[€/tCO_2]	133	20 €	85 €	350 €	2.5€
Renovation rate	max share/year	77	0.5%	1.50%	7.5%	.125%
Hydrogen import price	[€/kg H_2]	88	1.2 €	N/A	10 €	.1€/ kg H_2
Modal shift		77	80%	100%	120%	0.5%
RES costs	for solar & wind	145	80%	100%	150%	2.5%
Biomass availability		81	50%	100%	150%	.125%
Total		1591				

The step size for each sensitivity has been chosen to keep the distribution of sensitivities as even as possible. In some cases, (e.g., for energy demands), the sensitivities are applied for a number of sectors or technologies, both separate, as well as in combinations (e.g., demand developments in only the industry sector versus demand changes across both industry and transport). This leads to a higher total number of runs, while the step size remains the same.

6.3 Results

This section will present some general findings from the range of model runs, with some meta analysis across noteworthy sensitivities. Subsequently, the four most commonly and widely discussed potential barriers and opportunities will be analyzed and put into context of our modeling results.

6.3.1 General findings

The general results across all 1591 computed sensitivities show a clear trend for the German energy transition. Emissions heavily decline across all sensitivities, albeit with varying intensity. While the base case manages to achieve the German policy goal of 85 to 95% with a reduction of 88.4% compared to 1990 values, some sensitivities only achieve 75% emission reductions (see Figure 6.2).

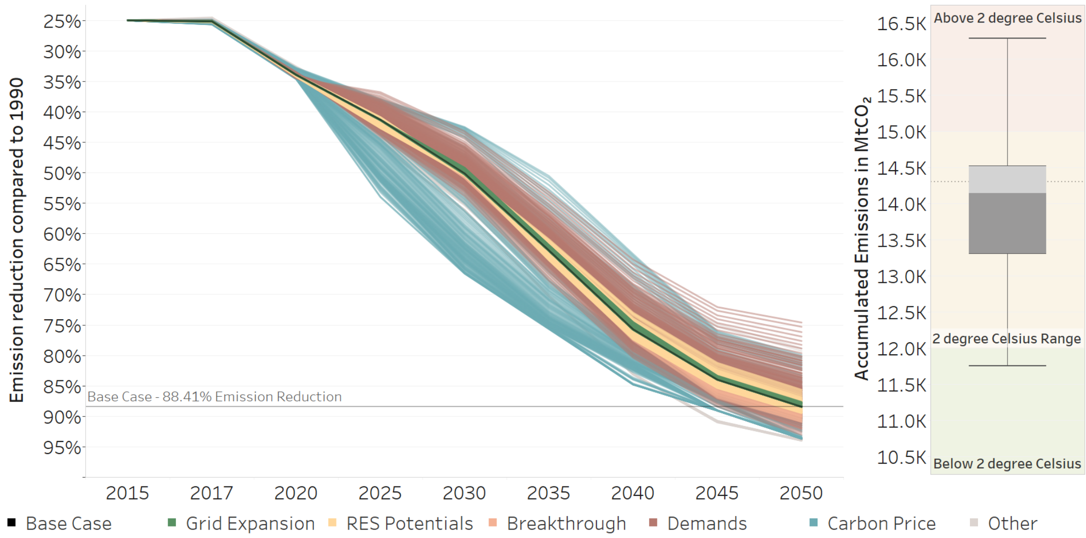

Figure 6.2: Spread of emission reductions compared to 1990 across all tested sensitivities (left) and spread of accumulated emissions in 2050 across all sensitivities. The range for the emission budgets is derived from the IPCC SR1.5 with a share for Germany based on its population.

While most sensitivities (including the base case) therefore fall in the 2° C range for global warming, some outliers above and below 2° C can be observed. However, these outliers are noticeably skewed towards the upper end, signaling an increased risk of failure to uphold the 2° C target within the computed sensitivities. The same shift towards renewable-based and thus emission-free technologies can also be observed in the electricity sector, with a drastic increase in RES-based electricity generation, as shown in Figure 6.3. The base case achieves a value of 95.9% renewables in electricity generation, with sensitivities ranging in between 100% and 78% renewable electricity. As with the emission reductions, the largest spread can be seen in the demand and emission price sensitivities.

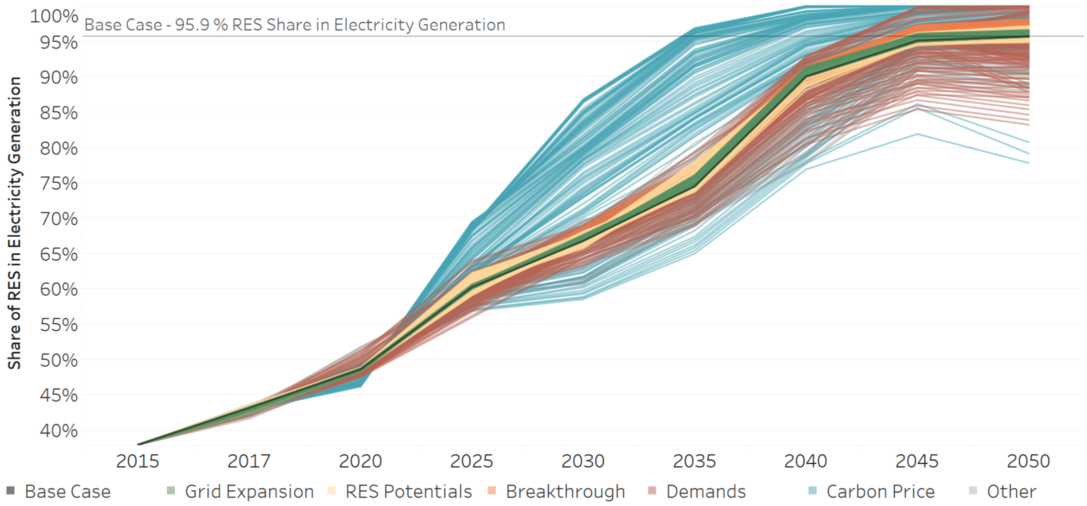

Figure 6.3: Spread of the share of renewables in electricity generation across all tested sensitivities.

The development of power generation costs, however, shows less of an influence of demands and emission price, and instead a strong reliance on exploitable renewable potentials and costs of renewable technologies (Figure 6.4). The emission price sensitivity is mostly noticeable in the intermediate future, and, contrary to popular opinion, we find only a marginal change in power generation costs when limiting the expansion of the electricity transmission grid. Looking at the state level, significant differences between German federal states can be observed in 2050. While some states only experience minor spreads of generation costs across all sensitivities, some states, such as Baden-Württemberg, Saarland, North-Rhine-Westfalia, and the city states Hamburg and Berlin experience a major spread in resulting electricity generation costs. Generation costs in Baden-Württemberg, for example, range between 25 and 78 € per MWh in 2050, leaving a threefold increase between lowest and highest sensitivity results. Except for the worst sensitivities regarding renewable technology costs, the generation costs for electricity experience a decline over time, with the base case reaching costs of 32€ per MWh in 2050, down from 52.5€ per MWh in 2015.[3] On a positive note, the results indicate that even in the 'worst case' sensitivity, generation costs remain at 2015 levels, contradicting a commonly found fallacy that a large-scale introduction of renewables comes at an increase in electricity costs.

[3]Please note that these only represent the pure generation costs of electricity. Transmission, storage and infrastructure costs are not included in these numbers.

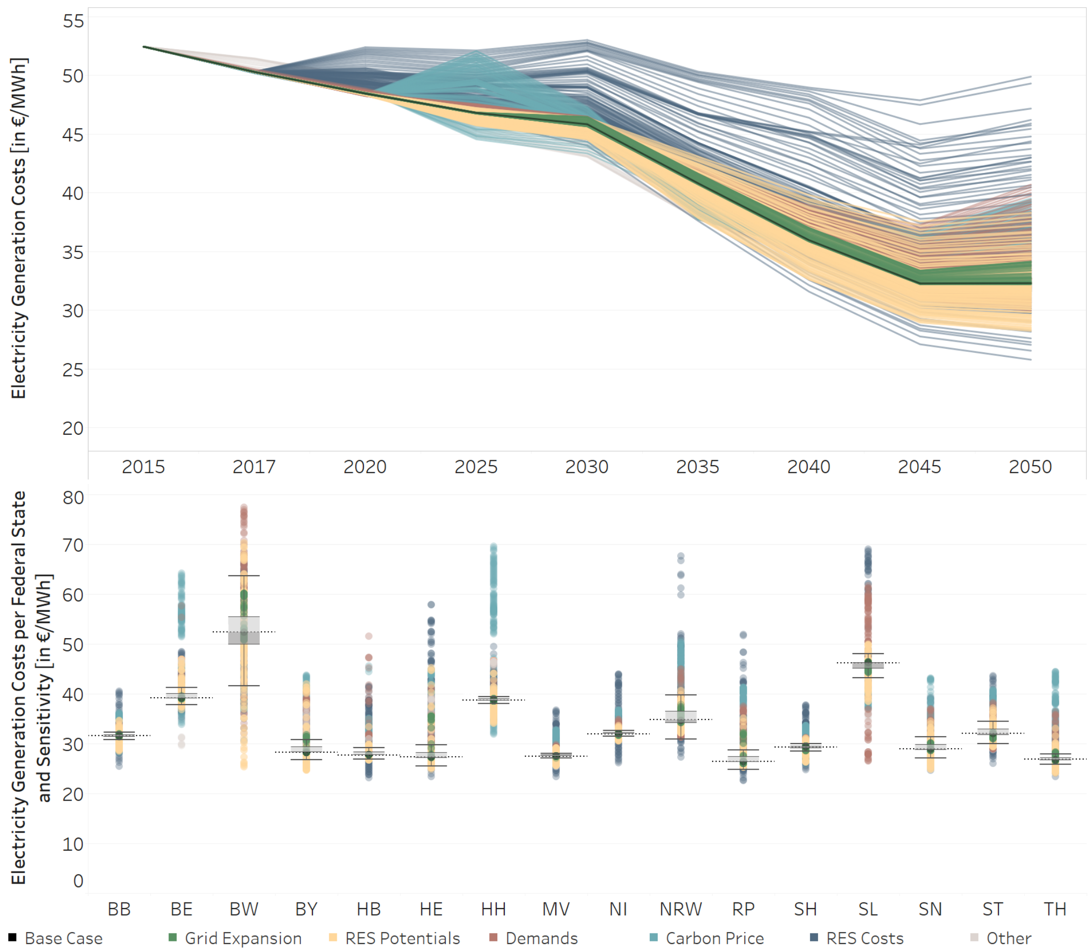

Figure 6.4: Average generation costs for electricity across all tested sensitivities. The top graph shows the development over time for Germany as a whole, the bottom graph shows the spread of electricity generation costs in 2050 per federal state. The costs are displayed in € per MWh and do not factor in infrastructure costs.

6.3.2 Demands

One of the key drivers of the transformation of the energy system is the overall energy demand. This is especially true in a post-COVID world, dominated by economic recovery and green investments (IEA 2020b). As outlined by Zaharia et al. (2019), primary and final energy consumption are affected by a multitude of factors and for some of them conflicting results are found in the literature, which in turn highlights the importance of including energy demand in this sensitivity analysis.

Across all sensitivities, altering the various demands of the sectors proved to have one of the most significant effects with respect to various key indicators. On the one hand, increasing (or decreasing) the input demand consequently comes with and increase (or decrease) of final energy consumption in the respective sectors. On the other hand, the sectors react differently with respect to the share of energy provided by electricity based technologies. This effect is illustrated in Figure 6.5, where the range of results is shown for the case where only the electricity demand is being analysed (top) and the case where all sector demands are considered (bottom).

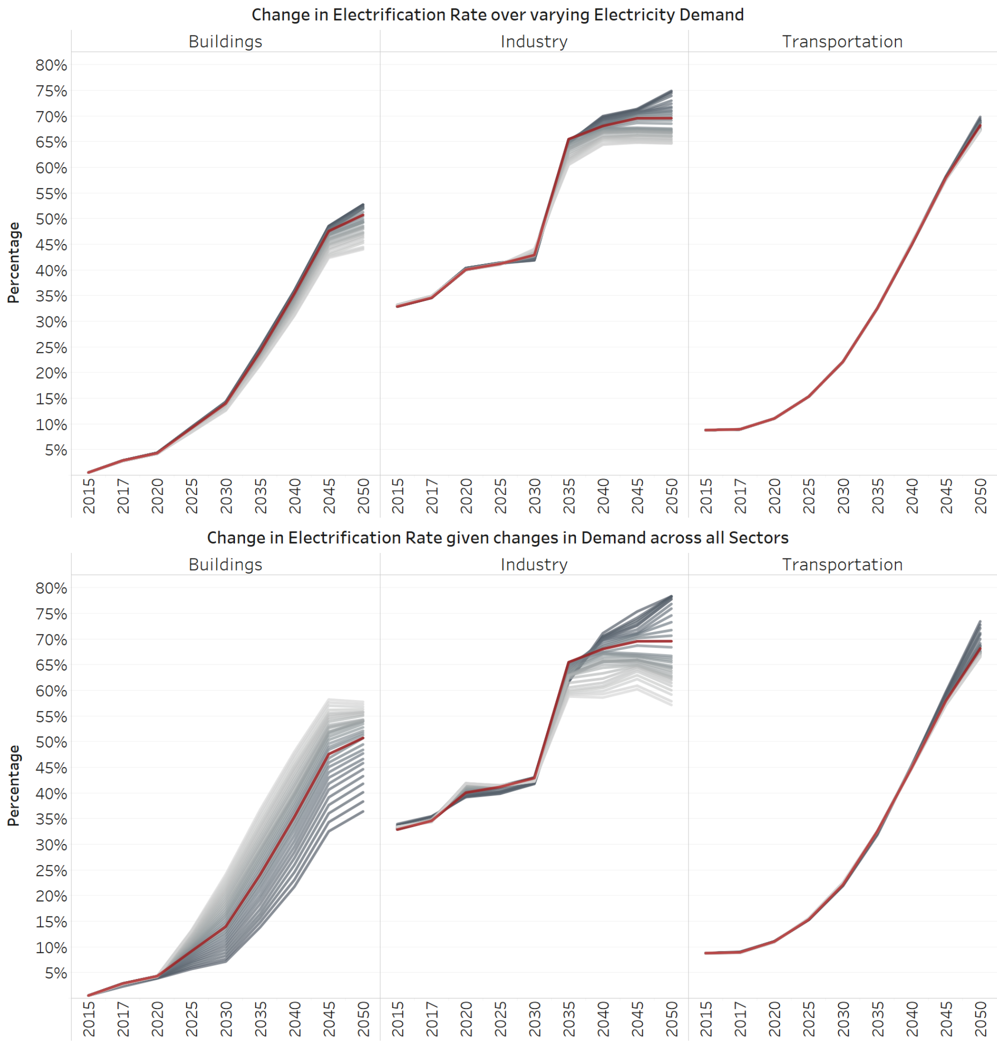

Figure 6.5: Changes in electrification rates by varying electricity demand in building, industry and transport sector (figure above). Changes in electrification rates by varying total energy demand in building, industry and transport sector (figure below).

The top half of the figure shows the industry sector being the one most affected by a change in the electricity demand. Less electricity demand means more electricity which can be used in other sectors and the industry sector seems to be the one where, despite the overall high level of the electrification rate, this effect is the strongest. In contrast, the other two sectors, transportation and buildings, show less variability in their electrification rate. This observation implies two aspects: First, the industry sector is the most difficult (or expensive in model terms) to electrify, as a reduction in available electricity leads to the reduction of electrification rate in the industry sector instead of the other two. Second, the sectors buildings and transportation seem to have reached a very stable state in the base case. Another observation is that the effect on the industry sector in 2050 is more or less symmetrical around our base case, while the buildings sector reacts stronger to an increase of electricity demand (reflected in the reduced electrification rate in the buildings sector) and the transportation sector is more affected, although only slightly, by decreasing electricity demand. These tendencies are amplified when analyzing the bottom half of Figure 6.5, where the range of results widens in general. The electrification rate in the transportation sector still seems to be less affected by varying demands than for the other two sectors. The buildings sector, on the flip side, now shows effects as early as 2025 which is caused by the installation of heat pumps at a rapid rate, regardless of the overall demand development.

Another indicator with significant results for the demand sensitivity is the amount of electricity production. In fact, out of all sensitivities, demands had the strongest effect on this indicator. As explained in the previous paragraph, all sectors experience significant rates of electrification and, therefore, electricity generation is strongly affected by demand changes across all sectors, as the overall electricity production is determined endogenous and consists electricity consumption for heating and transportation purposes as well as the residual power demand which is used for lighting, appliances, etc. The effects can be seen in Figure 6.6, which shows a wide range of outcomes where in 2050 the results range from 650 TWh to almost 1,200 TWh. An interesting development can be seen in the years 2020 - 2030 showing decreasing electricity production for the sensitivities with lower demand (darker shades). This can be explained by a slow uptake of electricity-based technologies across the sectors until 2030, such that the demand reduction dominates the additional power demand. In the later periods though, electricity becomes substantial in all sectors, overcompensating the demand reductions even in the most ambitious sensitivities.

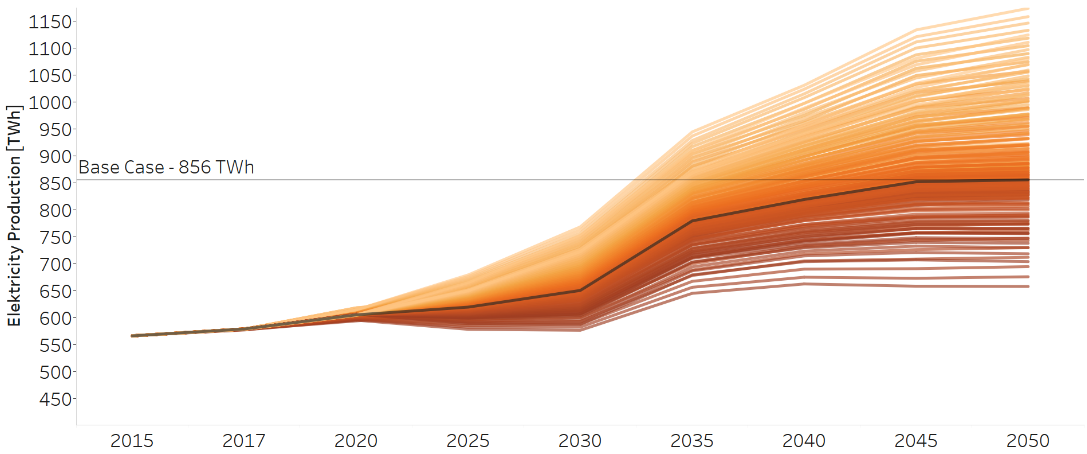

Figure 6.6: Effects of demand development sensitivities on electricity generation (in TWh).

6.3.3 Carbon price

As already outlined in Section 6.1.2, the discussion about a successful transformation of the German energy system sparked a debate about the dimension of an appropriate carbon price. Starting in 2021, Germany put in place a CO_2 price of 25 €/ton for the sectors heating and transportation (excluding aviation) which will increase up to 55 €/ton in 2025. After this 5-year period, a cap and trade system is planned with the amount of certificates being determined by agreed on climate targets. While leading research institutes in Germany deemed the general structure of the law to be a suitable tool in facilitating the *Energiewende*, the carbon price in particular was criticised in being too low to have a meaningful effect (Bach et al. 2020; Edenhofer et al. 2019a). This debate raises the need for a more in-depth analysis of the impacts of a carbon price on the German energy system transformation and through the sensitivity analysis on said instrument (as described in Section 6.2.4) light is shed on its effects on the different energy sectors.

To analyze the effects of a carbon price, the changes in the electrification rate of the different sectors will be analyzed again. For this modeling exercise, a uniform carbon price is assumed across all sectors disregarding possible slight differences between the German carbon price and the EU-ETS. Similar to the demand sensitivity, the transportation sector remains unaffected by a change in carbon price compared to a higher susceptibility observed in the buildings and especially the industry sector (Figure 6.7). This hints at higher difficulties for the decarbonization of certain parts of transportation, especially in freight transportation. While in the later years of the modeling period the effects in the industry sector are nearly symmetrical, a higher carbon price also shows effects in the earlier years, showing a massive uptake in electrification (and therefore mostly carbon free energy) caused by high carbon prices. Vice versa, a low carbon price leads to fossil fuels staying in the industry mix with only a small percentage being phased out until 2050. Overall, the results in the industrial sector in 2050 range from 55% to almost 80%. The buildings sector seems to be less affected which suggests that renovation rates (as in the demand sensitivity in Section 6.3.2) are more effective in electrifying the sector than a carbon price. Moreover, a carbon price has less of an impact in the buildings sector in the long term since the potential of heat pumps is already exhausted to a high degree in the base case.

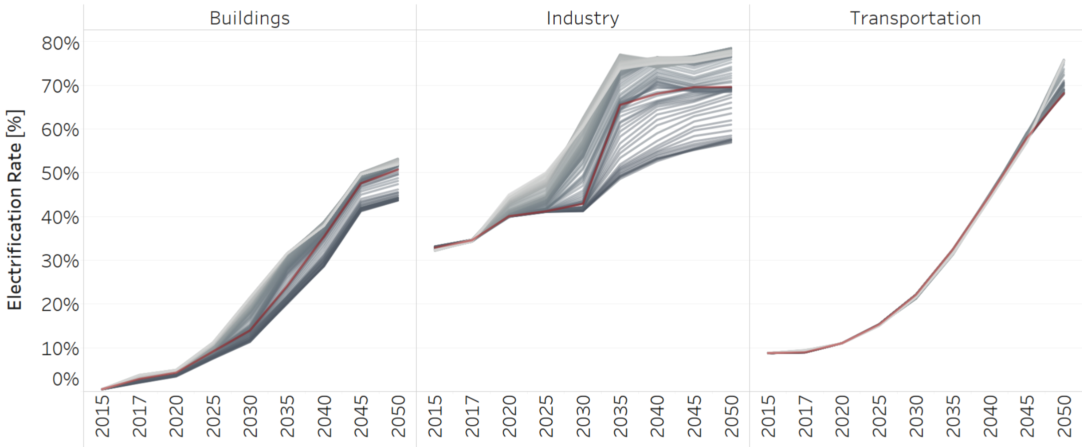

Figure 6.7: Effects of emission price sensitivities on the electrification rate across different sectors.

6.3.4 Hydrogen

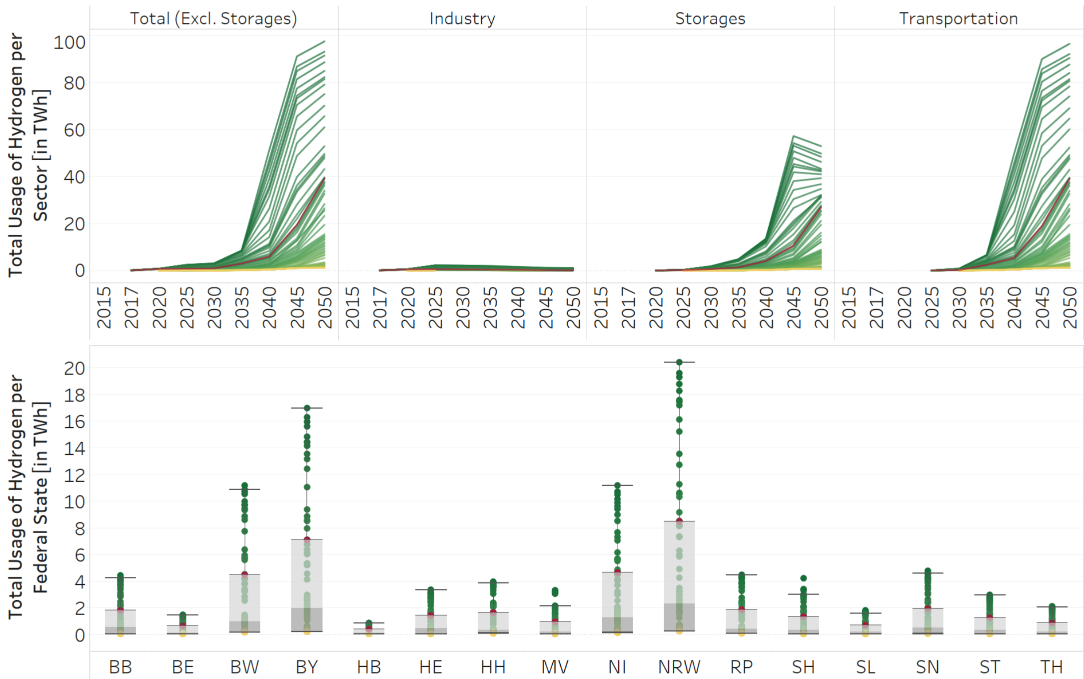

Figure 6.8: Usage of hydrogen per sector (top) and usage of hydrogen per federal state in 2050 (bottom) by varying costs for breakthrough technologies.

Hydrogen offers a great potential for the decarbonization of the energy system, from being a storage medium in the electricity sector to replacing processes in industry, which are difficult to electrify, or powering vehicles, especially heavy-duty ones. The potential and effects of hydrogen and subsequently sector coupling where analyzed extensively by Ausfelder et al. (2017). In recent years, national and EU-wide hydrogen strategies were developed across the continent, with Germany labeling it a "key element in the transformation of the energy system" (Bundesregierung 2020b). Therefore, in this paper the usage of hydrogen in the different sectors as well as the regional distribution of hydrogen consumption are discussed.

In general, a greatly varied hydrogen consumption can be observed, changing various input parameters. The hydrogen consumption in the transportation sector is particularly sensitive to varying costs for breakthrough technologies, as depicted by Figure 6.8. With highly reduced costs for hydrogen generating technologies, the consumption of hydrogen in the transportation sector nearly doubles, whereas the consumption in the industrial and buildings sectors stay close to base-case levels. In particular, significant cost reduction of fuel cell electric vehicles could lead to these vehicles being the dominant technologies for passenger cars, a field otherwise dominated by BEVs in the calculations. Freight transportation, on the other hand, is less sensitive and already in the base case relying heavily on hydrogen for road transportation.

With increased production of hydrogen and consequently its consumption, additional storage capacities for hydrogen are needed, as hydrogen is preferably produced in hours with excess renewable energy sources. Due to the late commercial availability of hydrogen transportation technologies, significant effects of changed breakthrough costs arise from 2035 on-wars, with 2025 and 2030 staying close to base-case levels for all sensitivities. With overall increased costs for breakthrough technologies, the overall consumption of hydrogen in all sectors decreases. However, even with the highest increase of breakthrough costs, small amounts of hydrogen are still used in the transportation sector, as for certain use-cases hydrogen poses a valid alternative for direct electrified transportation technologies or biofuels.

6.3.5 Renewable energy sources

Renewable energy sources are also a widely discussed topic regarding the low-carbon transition. While consensus has been reached that they are an important cornerstone to reduce emissions, there is widespread discussion about their optimal share in the energy mix, as well as about effects on e.g. power generation costs, energy security, or socio-economic factors such as jobs (Ram, Aghahosseini, and Breyer 2020; Oei, Hermann, et al. 2020; Brauers and Oei 2020). In this paper, two main uncertainties are discussed, the costs of renewables, and their potentials.

6.3.5.1 Costs of renewables

As already highlighted in section 6.3.1, the costs of renewable technologies largely influence future electricity generation costs. With a global political push away from fossil fuels towards renewables to fulfil set carbon reduction goals, RES are the only option for decarbonization apart from negative emission technologies (which themselves face huge uncertainties and risks (C. v. Hirschhausen, Herold, and Oei 2012; Anderson and Peters 2016)). Therefore, their costs inevitably have a strong influence on overall costs and, therefore, cost-optimized model results. It can be observed that given an increase in solar and wind costs of the 'worst-case' scenario, electricity generation costs would almost stagnate at 2015 levels. An increase of wind costs influences results quite more significantly than that of solar, as shown in the upper part of Figure 6.9, which is in line with similar research in the field (Gils et al. 2017; Pehnt, Oeser, and Swider 2008). The costs of wind turbines also significantly influence the amount of electricity trade within Germany, highlighting that solar energy potential is more evenly distributed across the regions compared to wing potential. While in the base case, the state of Lower Saxony proves to be a large net exporter of electricity (especially to the densely populated state of North-Rhine-Westfalia), an increase of wind costs leads to a more even distribution of electricity generation across Germany, but at a noticeably higher cost. Offshore wind plays a large role here, as Lower Saxony has abundant wind-rich coastal areas. However, even in a worse case characterized by RES costs higher than the ones assumed, although not declining, generation costs would not see an increase when compared to 2015 levels, which is a strong argument for RES as a no-regret option concerning future energy supply.

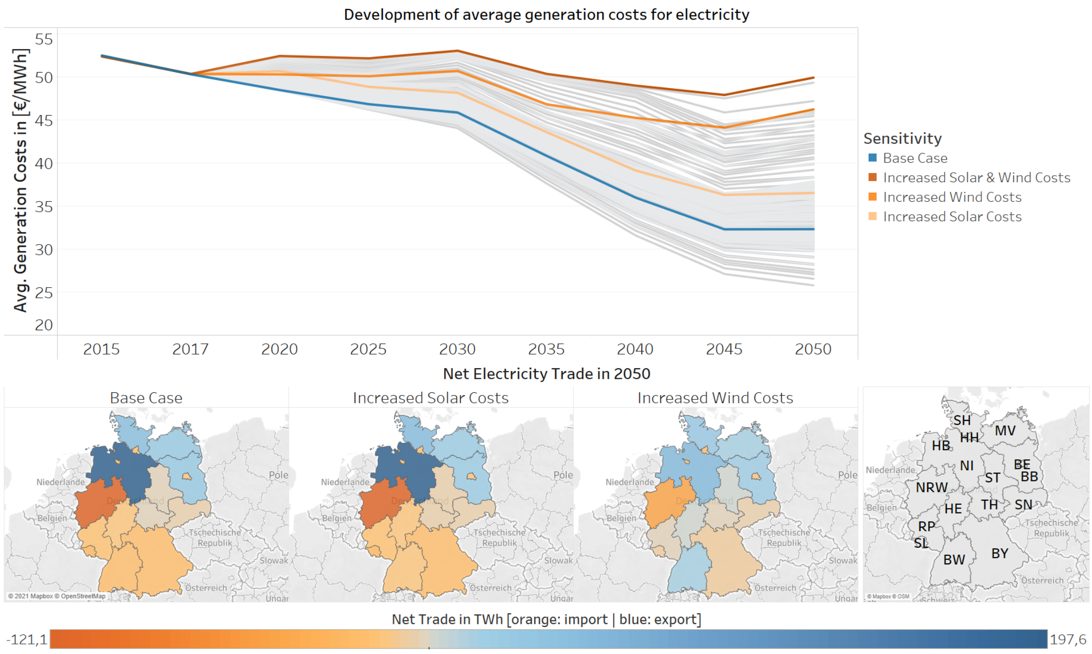

Figure 6.9: Development of average generation costs for electricity (top) and net trade of electricity in 2050 (bottom). Electricity generation costs in € per MWh, net trade in TWh.

6.3.5.2 Renewable energy potentials

Another commonly discussed topic is that of renewable potential. While the technical potential is usually quite abundant, economic viability and political barriers often significantly reduce these potentials. Policies such as the 10H rule as e.g. applied in Bavaria[4] shrink the available surface area for renewable installations. Especially wind turbines often face public acceptance issues, frequently related to the not-in-my-backyard phenomenon (Wolsink 2012). The sensitivity runs underline that importance, especially regarding the resulting cost-optimal technology mix and the distribution of installed capacities across Germany. Figure 6.10 shows the change in installed capacity for offshore and onshore wind, as well as solar, for each federal state. Overall, it can be observed that especially an increase in usable solar potential leads to more spread out PV installations and less offshore expansion in the three northern federal states. A similar effect can be noticed when onshore potentials are increased, albeit to a lesser extent, where offshore wind is reduced, mainly in Lower Saxony, in favor for onshore wind turbines across most parts of northern Germany. This hints at the role of wind onshore and solar gaining in importance and eliminating the need for baseload production offered by offshore if potentials were to increase, be it due to technological or regulatory developments.

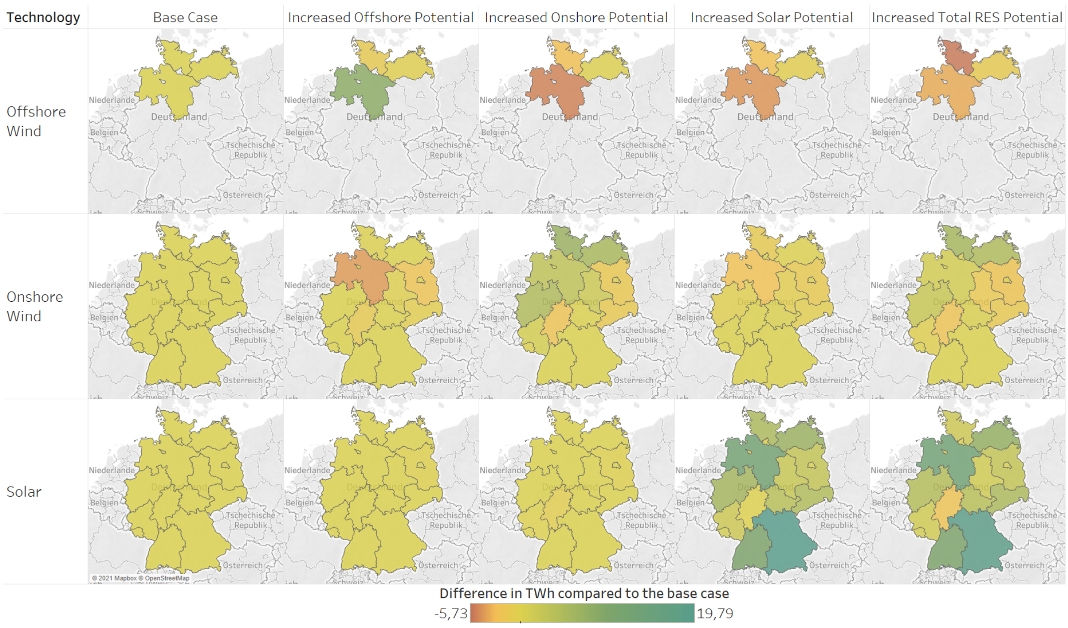

Figure 6.10: Electricity generation per federal state for offshore, onshore, and solar relative to the base case. Red color indicates less production than in the base case, yellow indicates no change, and green indicates an increase in generation.

Increasing all renewable potentials simultaneously results in the similar picture as only increasing solar PV potentials. This highlights that PV potentials seem to be a binding

[4]The 10H rule states that a wind turbine needs to be at least 10 times it's height from any populated area.

constraint in a number of federal states. Cross-referencing the results of said sensitivity shows a more decentralized German electricity system relying more heavily on solar and onshore wind, instead of large-scale offshore facilities in the Northern Sea. This also drastically reduces the need for new transmission capacities. Combined with an increase in the usable PV potential, if at all possible, a chance for a more distributed low-carbon transition across the country can be seen.

6.4 Conclusion

This paper uses the open-source energy system model GENeSYS-MOD to provide insights into key uncertain factors of the German low-carbon transition. For this, the newest version of GENeSYS-MOD has been used and adapted to Germany at a federal state level. A base case was defined as a reference for the exploratory sensitivity analysis. In total, 1591 sensitivities across 11 key influential factors have been computed. This allows for not only one singular pathway to be obtained, but a whole *scenario corridor*, highlighting the change in results with underlying changes of input assumptions. Therefore, it is possible to identify the most influential factors on the German *Energiewende* and how this translates to possible chances and potential barriers, depending on how the underlying parameters actually develop in the future. With such an exploratory sensitivity analysis, a wide view on possible pathways for the future of the German energy system can be obtained.

Results show that especially demand reduction plays a tremendous role in the process of reaching climate targets. Across all analyzed result values, changes in final energy demand heavily impacted the model results to achieve ambitious reduction targets by 2050, with an especially pronounced effect in the buildings sector. Also, the costs and available potentials of RES have a significant impact on generation costs, necessity of grid expansion, and the distribution of generation capacity across Germany. The choice of a price on emissions has a noticeable effect in the near to intermediate future, heavily reducing cumulative emissions since action is taken sooner, especially in the industrial sector. The costs of hydrogen are another noteworthy finding of this study: While usually mostly seen as a use-case in long-distance freight transportation and aviation, decreasing costs of hydrogen might open up usage across large parts of the transportation sector, including fuel-cell electric vehicles in passenger transport.

In general, it can be seen that an increase in energy efficiency, along with consumer-level demand behavior changes (e.g. in transport), could drastically help with the fulfilment of climate goals. However, further reductions of demands and an increase in sufficiency might be helpful to reach climate goals. Furthermore, a carbon price proves to be an efficient tool to reduce emissions in the buildings and industrial sectors. In these sectors a higher carbon price drastically improves overall electrification rates. Hence, the establishment of higher carbon prices in the near term could significantly reduce emissions and boost investment into renewable technologies. Nevertheless, the carbon price in this model can also be seen as a proxy for other climate policies that prove to be efficient in reducing emissions as well. As shown in our analysis, hydrogen and increased power trade capacities have also substantial potentials in decreasing emissions, although both show less effects on emission reduction than a decrease in demand. Overall, large-scale investments into renewable energies and storages are a no-regret-option for climate targets and often prove to be minimum requirements for other technologies.

Summing up, given the large amount of uncertainty in the results of energy system models, an extensive exploratory sensitivity analysis can produce meaningful insights. The spread in general results, as well as in effects for each parameter variation can be analyzed, giving an overview of key influential factors. For the analyzed German case study a reduction of 88% by 2050 (compared to 1990) was calculated, clearly missing the German (and European) target of climate neutrality. The obtained sensitivity pathways (changing always just one parameter) reach reduction values of 75 - 95% - showing that additional efforts in more than one domain are needed to allow for a faster decarbonization pathway. Thus, one can only underline the importance of immediate action that needs to undergo for the low-carbon transition to succeed. However, since many of the uncertain factors such as technological innovation, resource availability, and international trade (e.g. for hydrogen) go beyond the scope of a country-level analysis, further research should also look at implications on a global scale. Additionally, an expansion of the scope of the analysis, e.g. by broadening the range of analyzed sensitivities to also include socio-economic factors (such as behavioral aspects) would be beneficial. This would allow for a more holistic view over possible challenges, especially from a non-technical viewpoint. A further analysis could also inspect possible interdependencies and interactions between the different key factors, since this paper only focuses on the factors *ceteris paribus*. Finally, a combination and comparison of exploratory sensitivity analyses with Monte-Carlo simulation methods could provide additional insights on both effect on obtained results, but also on topics such as computational and model requirements.

Chapter 7

Identifying policy areas for the transition of the transportation sector

7.1 Introduction

Since the Paris agreement in 2015, emphasis around the globe has been put on reducing GHG emissions with the aim of keeping global warming below 1.5 °C or 2 °C compared to pre-industrial levels (UNFCCC 2015b). Yet, in its most recent report, the IPCC (2022) finds that global emissions kept rising until 2019 and that the current NDC are insufficient if the 1.5 °C target is to be achieved without overshooting the emission budget. Therefore, additional measures are necessary to facilitate the decarbonization of the energy system, which is responsible for the majority of global GHG emissions (IPCC 2022).
The transportation sector, as one of the energy sectors, is of particular interest, since it is the only sector in Europe and Germany with emissions still being higher or around 1990 levels (Umweltbundesamt 2022d; European Commission. Directorate General for Mobility and Transport. 2021). Currently relying heavily on fossil fuels (i.e. oil), the future transportation system will likely see more electrified options if GHG emissions are to be reduced. This, however, puts additional stress on the energy system, as the electricity required to power vehicles and trains needs to be produced through renewable energy sources and is also required for the decarbonization of other sectors like industry or buildings. Therefore, the field of energy system modeling experienced rapid growth over the last decade, motivated by the realization that an integrated analysis of the entire energy system is key for a future sector coupled energy system.

One apparent issue when analyzing future systems, no matter the domain, is the uncertainty that comes with it. Predicting the future is impossible yet trying to is necessary to gain insights into interactions and dependencies of the system of interest. The energy system will undergo a significant transformation in the upcoming years to achieve the targeted climate goals and future (uncertain) developments will have a strong influence on the shape of the transformation. Today, policy and decision makers need to put the regulatory framework in place which will facilitate this transformation, relying on analyses and predictions on the

This chapter is based on the single author work with the same title currently under review in *Energy Policy*.

effectiveness of their methods. And yet, even the most robust approaches when it comes to dealing with uncertainty will fail in predicting shock events which we can currently observe. The Covid-19 pandemic as well as the Russian invasion of Ukraine both have massive short term implications on the energy system (IEA 2022a, 2022b) which differ from what models predicted in the past. Therefore, developing an understanding of different energy system components and actors becomes even more important to be able to adapt to new situations while still being on the path of reducing GHG emissions.

Consequently, when analyzing possible futures and developments of the energy and transportation sector it is imperative to understand how the system is affected by different parameters which today are still uncertain. This work aims to answer the question of what are the impacts of key (uncertain) energy and transportation system parameters on the success of the German energy and mobility transition and which areas policy makers should target to generate the biggest impact. GENeSYS-MOD is applied to analyze a pathway of the German energy system until 2050 and in a second step complemented by a multitude of sensitivities highlighting the effect and leverage of specific input parameters on energy and transportation system related KPIs.
The following part of this paper presents the status quo of the German energy and transportation transition and policies (Section 7.2), as well as relevant literature (Section 7.2.1). Section 7.3 gives an overview of the applied model, methodology, and further assumptions, followed by Section 7.4 describing data sources and requirements. Following, Section 7.5 explores the results and discusses its implications as well as shortcomings of the methodology. Lastly, Section 7.6 concludes by stating policy implications and providing a brief outlook of future research needs.

7.2 German policy situation of the energy and mobility transition

In June 2021, the German parliament agreed on an updated climate protection law (german: *Klimaschutzgesetz*) which increased the GHG reduction targets to 65% in 2030, 88% in 2040 (both compared to 1990 levels) and GHG neutrality by 2045 (BMWK 2022a). In addition, sectoral emission reduction targets were also adjusted putting the burden on each sector to contribute to the overall reduction. And while overall emissions decreased by more than 35% between 1990 and 2019 (Umweltbundesamt 2022d), it seems unlikely that Germany can achieve its ambitious climate targets (BMU 2021b; Agora Energiewende 2022). According to BMU (2021b), GHG emission reduction targets and renewable energy share in electricity production miss the important milestones in 2030, 2040, and 2050 following the current trajectory. Furthermore, Agora Energiewende (2022) argue that the achievement of the 2020 climate targets was mainly caused by the Covid-19 pandemic, supported by the fact that the 2021 emissions increased again and, thus, missed the target.

The transportation sector is the only sector in Germany, where, despite climate efforts and targets, GHG emissions in 2019 were still around 1990 levels (Umweltbundesamt 2022f). The aforementioned sectoral emission reduction targets, however, demand a 48% reduction until 2030, which effectively has to be achieved within one decade (Umweltbundesamt 2022f). To achieve the target of 85 Mt CO_2e , the German federal environmental agency (UBA) proposed a variety of action blocks which target the regulatory, infrastructural, and economical framework (UBA 2022). Most of these blocks address road transportation since cars, trucks, and buses are responsible for 96% of total domestic transportation emissions (Eurostat 2022).

One often mentioned cornerstone of the successful decarbonization of the transportation sector is electric mobility. As of April 2022, about 700,000 cars in Germany are BEVs (Statista 2022a), making up less than 1.5% of total number of passenger cars (Statista 2022b). As a result, the declared target of 15 million BEVs by 2030 implies a substantial increase in sales as well as investments into charging infrastructure. Assuming 3.5 million newly registered cars per year, similar to pre-pandemic levels, almost every second vehicle would have to be electric in order to achieve the ambitious goal - a goal which according to a study by the Wuppertal Institut might still be insufficient to achieve the set climate targets (Koska and Jansen 2022).

Naturally, electric mobility is also relevant for other modes of transportation but is either already widely deployed (i.e. rail) or technologically not mature enough yet to be considered as a viable option within the next decade, as is the case for freight transportation. In the latter case, hydrogen and synthetic fuels could play a crucial role in defossilizing the transportation sector. While the overall efficiency of hydrogen is much worse compared to the direct use of electricity due to energy losses in the conversion process, its application in specific areas like heavy duty freight transportation or aviation could assist with the overall transformation (Staffell et al. 2019). However, with large-scale renewable hydrogen not being commercially available yet (Pareek et al. 2020), future cost and efficiency developments will play a crucial role determining the viability of hydrogen as a fuel.

Costs of fossil fuels also play a substantial role in the configuration of the transportation sector. Extraction, processing, and transportation of gasoline or diesel make up a sizeable share of the prices at gas station. The Russian invasion of Ukraine caused a significant increase in oil and gas prices, causing the diesel price in Germany to surpass 2€/l. But an even higher share consists of taxes for energy, value added, and carbon emissions (ADAC 2022), which in the case of diesel is further subsidized. Among other things, removing subsidies for fossil fuels and increasing the carbon price are measures which are cited to enable the transformation of the transportation sector (UBA 2022; Agora Verkehrswende 2018). With higher shares of electric mobility, the amount of tax income will, on the one hand, be reduced due to less demand for fossil fuels. In the intermediate term, these losses could be compensated by the removal of fossil fuel subsidies and an increased carbon price (ElektroMobilität NRW 2022). Long-term, vehicle taxes or other taxing mechanisms addressing the use of road infrastructure could serve as compensation.

7.2.1 Review of Relevant Literature

Various studies and articles exist which analyze either the future German transportation sector in a decarbonized energy system or policies on how to achieve it. With the updated climate targets set by the new German government in 2021, multiple long-term scenario studies analyzing the pathways towards GHG neutrality in 2045 were published in the past months (BCG 2021; Krail et al. 2021; Luderer, Kost, and Sörgel 2021; Prognos, Öko-Institut, and Wuppertal-Institut 2021; Dena 2021). While scenarios and assumptions differ, all paint a picture of quick decarbonization of all sectors, including the transportation sector which is rapidly electrified. Since all studies target full decarbonization until 2045, strong assumptions on transportation demand were made.

In a comprehensive overview of multi-sector energy transition scenarios for Germany, Naegler et al. (2021) show that for 26 scenarios by different studies aiming for at least 90% GHG reduction until 2050, BEVs dominate road transportation in 2050 while results for freight transportation often lack in degree of detail. In general, future technology diversity in the transportation sector is projected to be much more pronounced than today. Bartholdsen et al. (2019) and Löffler et al. (2022) both analyze the transportation sector as part of a decarbonized energy system. Electrification is found to be a cornerstone of the transformation of the transportation system, coupled with high amounts of renewable energies. Additionally, Löffler et al. (2022) find that demand reductions show high potentials for overall emission reductions. Recently, Ehrenberger et al. (2021) provided scenarios which analyze the emissions of the transportation sector until 2040 given three different scenarios which assume different levels of technological and regulatory development. They conclude that heavy electrification and decarbonization of the electricity sector is required for GHG reductions in the transportation sector, yet none of the scenarios reached GHG neutrality despite strong assumptions (Ehrenberger et al. 2021). Similarly, Winkler and Mocanu (2020) find that technological development is important to decarbonize road transportation which will remain the most important mode of transportation. The authors point out that measures which reduce transportation or shift it towards more efficient modes have the highest effects on reducing transportation emissions.

Furthermore, Wicki, Fesenfeld, and Bernauer (2019) highlight that policy acceptance does not necessarily depend on the type of policy but rather the context. In their experiment the authors find that reduction in public transport prices and income tax, coupled with an increase in fuel prices and taxes and eliminating fossil fuel subsidies shows high support. Peiseler and Cabrera Serrenho (2022) show that current policies do not make full use of the potential of electric vehicles and propose ways on how to adjust these policies in order to facilitate the decarbonization of road transportation.

All of these findings tie into the A-S-I approach (Avoid-Shift-Improve) which was developed in the early 90s in Germany which "... serves as a way to structure policy measures to reduce the environmental impact of transport and thereby improve the quality of life in cities" (GIZ 2019). *Avoid* refers to reducing demand for transportation by either better transport or city planning. *Shift* focuses on improving individual trip efficiency by shifting transport from the most energy consuming and polluting modes of transportation to more environmentally friendly ones. Lastly, *improve* targets vehicle efficiency as well as the entire value chain of fuel generation. These categories play an important role on the shape and effectiveness of transportation policies and the discussion in Section 7.5.3 will analyze which policies and respective areas show the strongest effects.

Overall, most of the literature focuses either on the transportation sector and related policies or on the energy system as a whole with insufficient degree of detail when it comes to transportation. This work tries to bridge this gap and highlight policy effects in the transportation sector, tied to the Avoid-Shift-Improve approach, while keeping interactions with the rest of the energy system in mind. Further, all data and model source-code is publicly available, contributing to open science and allowing other researchers to reproduce the findings and further contribute to this topic.

7.3 Methodology

For the present work, the Global Energy System Model (GENeSYS-MOD) is being used as a tool to analyze future pathways of the German transportation and energy sector. The following sections briefly introduce the framework, highlight improvements made to GENeSYS-MOD for this study as well as describe the sensitivity analysis approach.

7.3.1 GENeSYS-MOD and model setup

GENeSYS-MOD is an open-source energy system model which is tailored towards long-term energy system transition pathways and based on OSeMOSYS.[1] Since its first publication in 2017 (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017), it has been applied in numerous case-studies and projects (e.g. Germany (Bartholdsen et al. 2019), Europe (Hainsch et al. 2021), South Africa (Hanto et al. 2021a) or Japan (Burandt 2021)). With the different energy sectors becoming increasingly connected in the future energy systems, due to sector coupling and electrification, GENeSYS-MOD analyses these sector interactions by simultaneously optimizing investments, energy generation, and dispatch while considering regional particularities and possible climate policies. Figure 7.1 illustrates a simplified structure of GENeSYS-MOD.

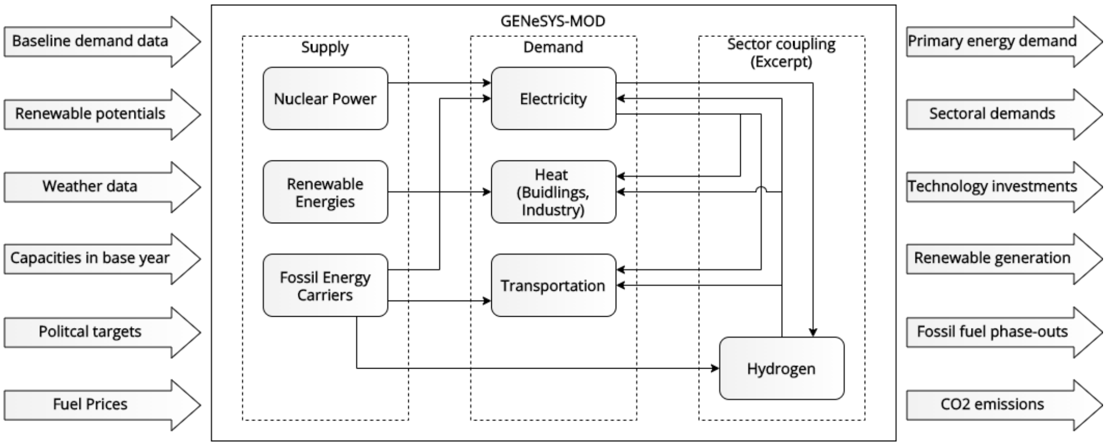

Figure 7.1: Representation of inputs, model components, and outputs of GENeSYS-MOD

The work presented in this article builds upon previous iterations of GENeSYS-MOD which analyze the German energy transition under specific scenario assumptions (Bartholdsen et al. 2019) and highlight chances and barriers of said transition (Löffler et al. 2022). Especially the sensitivity analysis carried out in the second article is extended now to the transportation sector and described in more detail in Section 7.3.3. Germany is split into its 16 federal states and the analysis is carried out starting in 2015 until 2050 in 5 year steps. The year 2017 is added and together with 2015 and 2020 serves as a base year for calibration purposes. With the year 2020 being dominated by the Covid pandemic, the effects are also reflected in the energy system in the form of reduced demands for all energy services. Nevertheless, it is included in the analysis due to its implications on the subsequent years. Post-Covid recovery assumptions consist of 2022 reaching the same

[1] For further information on GENeSYS-MOD including a documentation, quick-start guide, and a sample data set, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public

demand levels as pre-pandemic and a linear continuation towards the demand projections in 2045. Since investments, generation, and dispatch are optimized simultaneously for all years, the sub-annual resolution has to be reduced to not run into computational challenges. A timeseries-clustering algorithm, described in Gerbaulet and Lorenz (2017) and Burandt et al. (2019), was applied which reduced the timeseries to every 74$^{\text{th}}$ hour, resulting in 118 time steps per year which take daily and seasonal variations of demand and generation into account.

7.3.2 Improvements to GENeSYS-MOD

Since its first iteration in 2017, no structural changes have been made to the transportation sector in GENeSYS-MOD. Therefore, the degree of detail of the transportation sector, specific functionalities, and usability were updated for the present work to allow for more in-depth analyses.

Originally, transportation demand was split between freight and passenger transportation with a number of different modes (i.e. road, rail, and air/ship for passenger/freight respectively) and corresponding technologies for each of the two. For the present work, public transport in the form of buses and short-distance trains was added to the modal types to better illustrate the different options for passenger transportation, especially in urban areas. Initially, it was also planned to disaggregate road freight transportation into light-duty and heavy-duty vehicles as they serve two different purposes as well as offering different technological possibilities. However, vehicles under 20,000 kg maximum weight, which light-duty vehicles belong to, only make up 2.7% of total road transportation according to the Federal Motor Transport Authority (Kraftfahrtbundesamt 2021). With road transportation therefore being heavily dominated by heavy duty vehicles in terms of transportation amount and, thus, also emissions, this mode was left untouched. Other modes of transportation which are not energy dependent, like biking or walking, lack direct interaction with the energy system and are therefore not considered. Assumptions about these modes are made and taken into account when determining the overall transportation demand, however. Figure 7.2 illustrates the technology landscape and demand structure of the updated transportation sector in GENeSYS-MOD.

Next, the structure of the implementation of BEVs was updated. Originally, BEVs were treated like overhead-powered trains, meaning that the electricity required to fuel the vehicles was produced at the same time it was consumed. As a result, the flexibility potential of BEVs was underestimated. With the new implementation, all battery electric vehicles (i.e. cars, trucks, and buses) are connected to a storage unit which can be charged at any time and provide the required electricity at a later point in time. It is noteworthy that

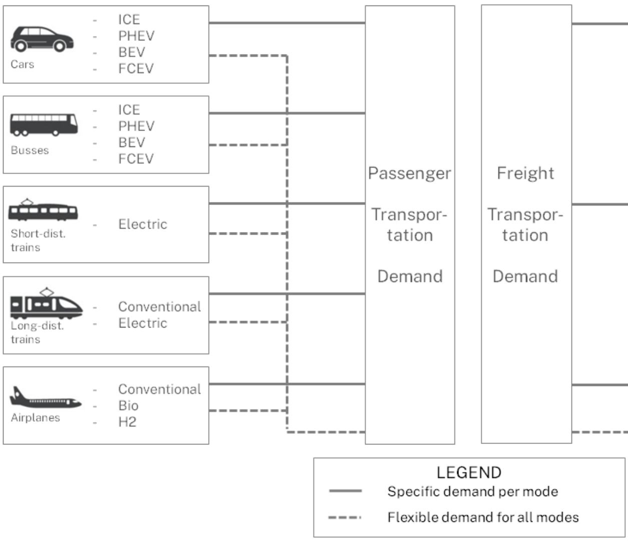

Figure 7.2: Structure of updated transportation sector in GENeSYS-MOD

for the current work charging patterns are subject to the optimization and can therefore differ from currently observed charging behaviour which is mainly consumer determined (Element Energy 2019).

Another change in design was implemented with respect to how transportation demands are considered in the model. In the previous iterations, two demands were specified (freight and passenger) and for each demand a modal split was defined for each year, stating how much of the respective demand had to be covered by which mode of transportation. Within these modes, single technologies were then able to contribute to the required modal split and consequently demand. This formulation, however, required that if demand for a specific mode of transportation was to be altered, all other modes were also affected or at least had to be considered. With the new formulation, each mode of transportation has its own demand which can be modified independently, making scenario analyses and data acquisition and implementation more user-friendly.

In addition, a flexible demand for passenger and freight transportation was added which can be covered by all technologies which belong to passenger or freight transportation respectively. As a result, transportation demands exist for all modes of transportation (e.g., cars, busses, airplanes) and in addition a demand which can be covered by any combination of these modes. In 2030, it is assumed that 6% of the total transportation demand is of this flexible nature, with the share increasing until 2050. The modal choice in the model is mainly determined by cost minimization, and can not account for personal preferences of individuals when it comes to their choice of mode of transportation. However, the *improve* category of policies directly addresses this question, aiming at transferring transportation demand from less to more desired modes of transportation. Hence, the effect of this flexible demand is further highlighted in the sensitivity analysis in Section 7.5.

Lastly, more possibilities for the user to directly input data are provided. While the initial implementation of input parameters is still available if desired, the new version allows for directly inserting values for typical transport and vehicle parameters like annual vehicle driving distance, occupancy/load factor, fuel consumption per 100 km, or vehicle purchasing cost. Even though all of the mentioned parameters were already included in GENeSYS-MOD, they were part of more complex parameters and, as a result, not easily accessible for scenario or result analyses. The new implementation allows users to use more intuitive values which might also be easier to find data for, while keeping the old version in place.

7.3.3 Sensitivity Analysis

The objective of this work is to highlight the effect and leverage specific transport related policies have on the overall German energy transition. While it is agreed upon that the future energy system will have to look significantly different compared to today if climate goals are to be achieved, opinions differ on what this transformation will have to look like (Clack et al. 2017; Brown et al. 2018; Schill et al. 2018). With models being unable to predict the future, their strength lies rather in the comparison of results and the resulting generation of insights than in the provision of single numbers (Huntington, Weyant, and Sweeney 1982). As a result, uncertainties in the future energy system need to be considered when analyzing such a system, especially when communicating the results to policy and decision makers.

Several methodologies exist to address uncertainty in modeling. The most common ones either focus on directly addressing it through stochastic modeling (Birge and Louveaux 2011; Burandt 2021), applying limited foresight to the model (Gerbaulet et al. 2019; Löffler et al. 2019), or altering uncertain input parameters in the form of scenarios or a sensitivity analysis (Pfenninger, Hawkes, and Keirstead 2014; Hainsch et al. 2021; Löffler et al. 2022). In particular, sensitivity analysis describes the approach of changing single input parameters and observing the models behaviour, being able to directly attribute changes in the results to the parameter of interest. The disadvantage, however, consists of ignoring interactions between multiple different (uncertain) factors which are important in the real system (Ferretti, Saltelli, and Tarantola 2016). In this study, the methodology of exploratory sensitivity analysis will be used to quantify the effects of four different factors on the overall energy system and the transportation sector in particular. The aforementioned shortcoming will be kept in mind for the analysis and interpretation of the results, which nonetheless provide valuable insights into the effects and leverages of policies targeting the transportation sector.

The four factors which will be analyzed are the following: carbon price, transportation demand, hydrogen generation efficiency and costs, and modal shift. Carbon prices or taxes are widely regarded as a suitable tool to facilitate the low-carbon transition of energy systems (Baranzini et al. 2017; IPCC 2018), yet have to be treated with caution in terms of magnitude and uniformity (Verbruggen and Brauers 2020). Reducing transportation demand in terms of passenger or ton kilometer is another major lever to facilitate the low-carbon energy system transformation (Löffler et al. 2022), yet not analyzed as extensively in the energy system modeling literature as, for example, technological solutions (Dominković et al. 2018). Hydrogen has been, and is, considered by some as a significant driver in defossilizing the transportation sector (Berry et al. 1996; Chapman et al. 2019; Staffell et al. 2019). However, costs and efficiencies are prominently mentioned as limiting factors (Chapman et al. 2019; Staffell et al. 2019). Lastly, shifting transportation from energy and carbon intensive modes to lesser ones offers the possibility to reduce emissions and energy demand while at the same time providing the same amount of transportation services (Shah et al. 2021).

For this study, a base-case is modeled and used as a reference, taking into account current projections, phase-out targets, price and demand developments, etc. In a second step, parameters which can be attributed to one of the four aforementioned factors are slightly altered one by one to analyze their impact on the future energy and transportation system. 100 sensitivities are computed for each case, leading to a total of 400 deviations from the base case. Table 7.1 showcases which parameters were altered as well as the ranges for each of the four cases. Generally, maximum and minimum values for the parameters consist of the parameter's base value multiplied or divided by two, respectively. The exception of this rule is transportation demand, where due to its large effect a factor of 1.5 was chosen. Four big energy scenario studies conducted in the past years in Germany project the transportation demand to grow up to 10% until 2030 for passenger transportation and up to 20% for freight transportation (Luderer, Kost, and Sörgel 2021; Prognos, Öko-Institut, and Wuppertal-Institut 2021; Krail et al. 2021; BCG 2021). Therefore, using 1.5 as the sensitivity factor allows a more detailed representation of the relevant interval while still allowing to analyze a wide range of values. The 100 sensitivities per case are linearly distributed between one and the respective factor. Since the year 2030 is of particular interest due to several climate policies, the sensitivity factor is fully applied from 2030 on with half its effect being applied in 2025.

Table 7.1: Analyzed sensitivities, corresponding model parameters and intervals of values for the year 2030.

	Parameters	Min	Default	Max	Factor
Carbon price	Emission cost	40 €/ton	80 €/ton	160 €/ton	2
Transportation demand	Total demand for freight and passenger transportation	66.66%	100%	150%	1.5
Hydrogen costs and efficiencies	Efficiencies for hydrogen generating technologies	50%	67%	80%	2
	Costs of hydrogen imports	18€/kg	9€/kg	4.5€/kg	
Modal shift	Share of flexible transportation demand compared to overall transportation demand	3%	6%	12%	2

7.4 Data

For the analysis carried out in this study, data for various parameters had to be updated with the main reason being twofold: First, the expansion of the transportation sector by public transport required extensive data research on techno-economic vehicle parameters as well as regionally disaggregated demands for buses and short-distance trains. Second, the inclusion of 2020 as a reference year demanded the inclusion of energy capacities, generation, and demand not only for the transportation but for all energy sectors. Since the present study builds upon Bartholdsen et al. (2019) and Löffler et al. (2022), the reader is referred to these two articles for information on all data not described in the following sections.

7.4.1 Public Transport

Transportation demand for public transport was taken from the Federal Office of Statistics together with the occupancy factor for each German federal state (Statistisches Bundesamt 2022a). In conjunction with efficiencies for electric, hydrogen, and diesel buses (Infoportal NRW 2021a, 2021b; Berliner Morgenpost 2018), the efficiency per passenger kilometer per federal state can be calculated. Vehicle purchasing costs for buses are also taken from Infoportal NRW (2021b). Similarly, for short distance trains purchasing costs (Berliner Morgenpost 2012; Frankfurter Rundschau 2019), consumption (Deiters 2009), and the mentioned occupancy factors are used to compute the neccessary parameters.

7.4.2 Reference year calibration and demand projections

The inclusion of 2020 as a reference year requires data on demands for all sectors. However, with the Covid pandemic breaking out in the early months of the year, energy and transportation demand saw a substantial decrease compared to expectations (Mofijur et al. 2021; IEA 2020a). This atypical behaviour comes with two challanges: On the one hand, energy system models are not calibrated taking such drastic shocks into account and, as a result, need to be constraint heavily to represent these situations adequatly. On the other hand, data for all sectors and federal states is not fully available yet which usually leads to assumptions being made based on projections and similar developments. Since there is no prior experience on an event of such scale, these assumptions have to be treated with caution.

Power production per technology was taken from BDEW (2022) while demand for heating and industry was adjusted by the same factor due to a lack of available data. Transportation demand for 2019 was taken from the European Commission. Directorate General for Mobility and Transport. (2021) and adjusted for 2020 based on a report of Transport-Online (2021). Demand projections for up to 2045 were adopted from the Ariadne Report which analyzes pathways for Germany's decarbonization until 2045 (Luderer, Kost, and Sörgel 2021). With respect to post-covid recovery, the assumption was made that 2022 transportation demand are similar to 2019, with linear increase of demand afterwards towards the 2045 values.

7.5 Results

This section presents and analyzes the main results. First, the base case results will be highlighted describing the basis on which the sensitivities build upon. The second part focuses on the sensitivities and shed light on how sensitive the model results react by analyzing and comparing six energy and transportation sector related KPIs.

7.5.1 Base case results

The results of the base case describe a pathway towards a highly decarbonized German energy system with small amounts of CO_2 emissions left in 2050, thus missing the proposed target of no GHG-emissions by 2045. Figure 7.3 shows that the electricity sector is the quickest to be decarbonized, while transportation and buildings are responsible for the remaining emissions in 2045 and 2050. This rapid decarbonization of the electricity sector is key, since non-fossil options in the other sectors mainly rely on electricity which needs to be produced through renewable energies for an effective decarbonization. Overall, the target of 65% reduced GHG emissions in 2030 compared to 1990 is achieved. The respective carbon budgets, derived from the global carbon budgets stated by the IPCC (2021) AR6 WG1 report, are also depicted, representing a 66% chance to keep global warming below 1.5 °C and 2 °C, respectively. Since the stated budgets represent a global limit, the country budget for Germany was determined by the share of population for the purpose of this illustration. Figure 7.3 clearly shows that even as quick of a decarbonization as in the base case fails to come close to the 1.5 °C target, while still achieving the 2 °C target.

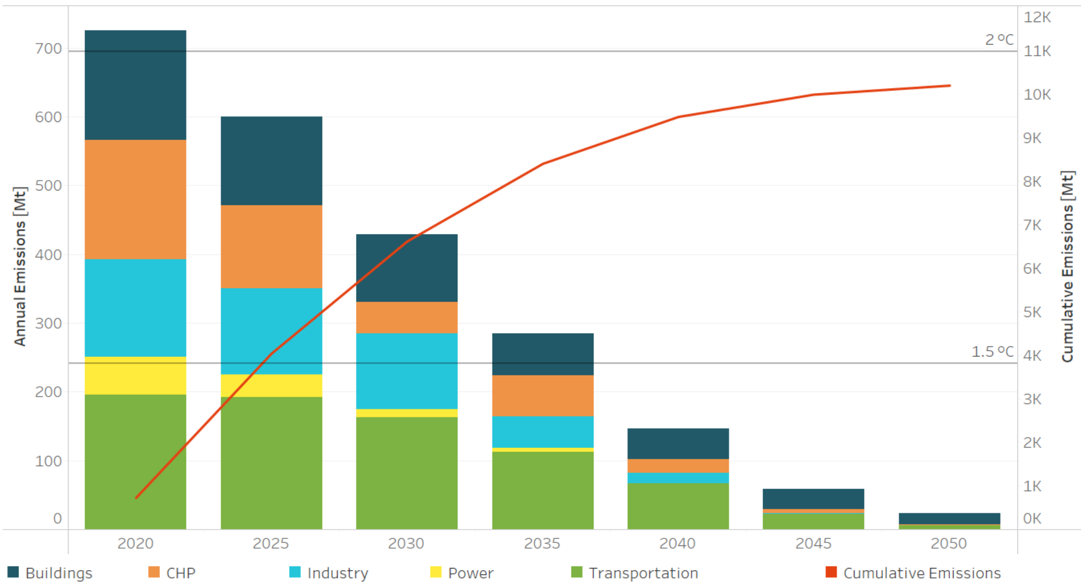

Figure 7.3: Annual emissions per sector (bars) and cumulative emissions (line) in the base case. Source: Own illustration.

This reduction in emissions is facilitated by a substantial increase in electricity production which, in turn, is caused by high degrees of electrification of the residential, industrial, and transportation sector. Contrary, primary energy consumption is reduced, with the reason being higher efficiencies of electricity-consuming technologies compared to their fossil-fueled alternatives. Figure 7.4 illustrates electricity production and primary energy consumption in the base case. Compared to 2015, electricity production almost doubles until 2050 with wind onshore, wind offshore, and PV contributing almost equally and supplemented by small amounts of bio-energy and hydropower. Wind onshore, and to a degree PV, is expanded rapidly in the early modeling periods, followed by wind offshore which takes off in the later periods. Fossil fuels, on the other hand, are quickly being phased out with coal and natural gas becoming irrelevant after 2040 due to their emission intensity and cost-disadvantages compared to renewables, while all nuclear power plants are shut down in 2022 following governmental plans. The declared political target of at least 80% renewable power generation in 2030 is achieved, caused by a faster expansion than currently observed and predicted based on the existing regulatory framework in BMU (2021b).

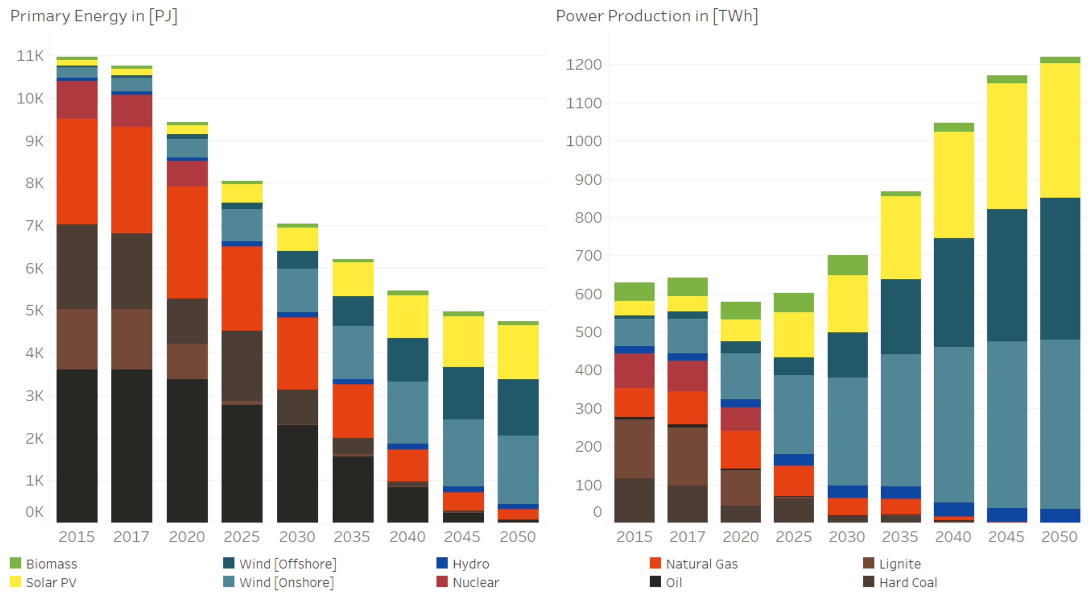

Figure 7.4: Primary energy consumption (left) and power production (right) in the base case. Source: Own illustration.

Crucially, no new fossil capacities are build as can be seen in Figure 7.5 which shows total and new capacities per year. While fossil capacities slowly disappear due to their expiration of lifetime, wind and PV capacities are quickly expanded by an annual rate of 16 GW combined until 2030 and up to 32 GW until 2040. Storage options become important in 2035 with lithium-ion batteries complementing the already existing pumped hydro storage.

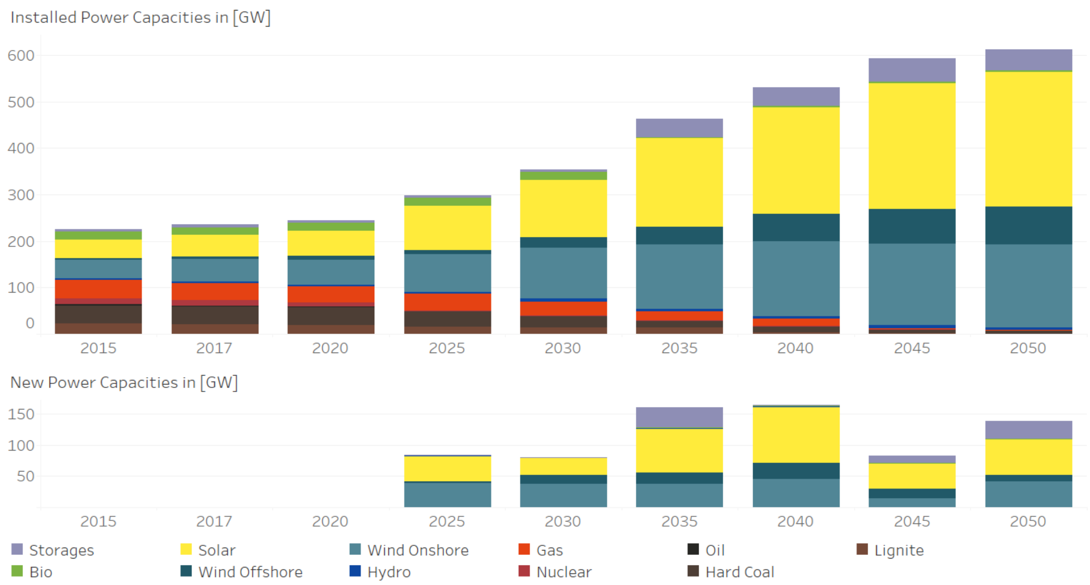

Figure 7.5: Total installed capacities (top) and new capacities (bottom) in the base case. Source: Own illustration.

Lastly, the results of the transportation sector will be highlighted due to their significance for the sensitivity analysis in the second part of this chapter. Figure 7.6 illustrates the technologies and their respective transportation volumes for both passenger and freight transportation. For the passenger part, a strong shift towards BEVs can be observed with about 20% of motorized private transport in 2030 and almost 100% in 2050. The 2030 value equates to almost 10 million BEVs which significantly misses the target of 15 million. However, with 20 million BEVs in 2035, this mark is missed only by a few years. Another trend for passenger transportation is the increased significance of public transport. Both buses and short distance trains provide almost all of the flexible transportation demand, highlighting their higher cost-effectiveness compared to cars. A similar trend can be observed in freight transportation where rail becomes more important for the same reasons. Since battery trucks are a non-factor, road freight transportation shifts towards less carbon intensity by first introducing plug-in vehicles fueled by bio-diesel and later H2-trucks replacing traditional diesel trucks.

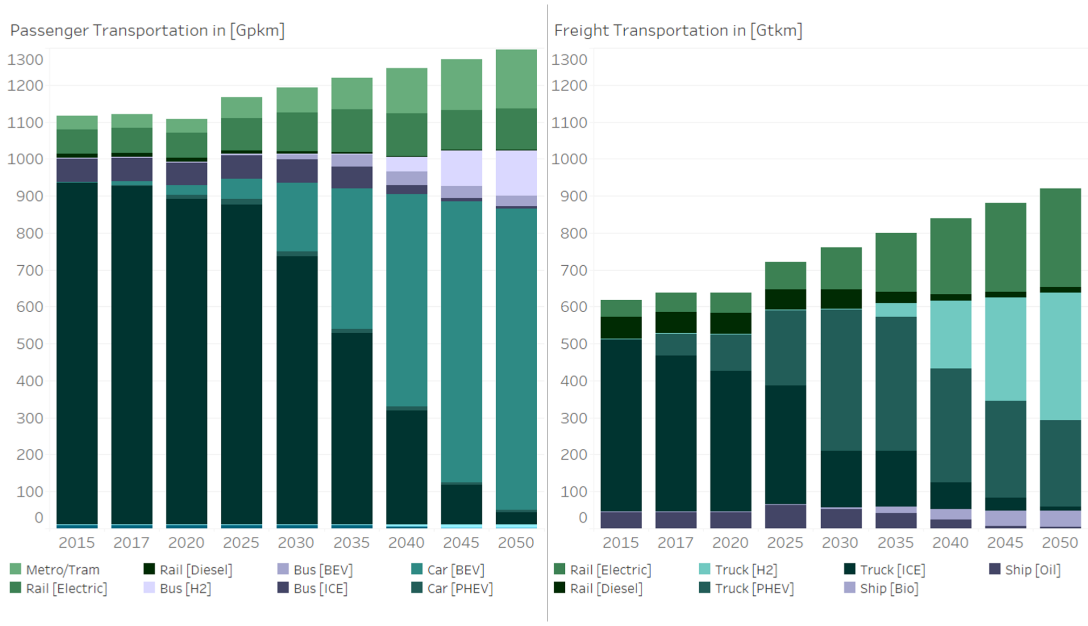

Figure 7.6: Passenger (left) and freight (right) transportation in the base case. Source: Own illustration.

7.5.2 Sensitivity results

As described in Section 7.3.3, four different cases are considered as sensitivities: *Carbon price*, *Demand*, *Hydrogen*, and *Modal shift*. For each of these cases, 100 sensitivities were calculated varying corresponding input parameters around the base case values (see Table 7.1 for an overview of the affected parameters and ranges). To allow for a comprehensive comparison of such a large number of model results, six KPIs are defined which will likely be important in the future energy and transportation sector:

- Total transport related primary energy consumption
- Total electricity production
- Total amount of transport related emissions
- Specific emissions of cars
- Number of cars
- Total hydrogen production and import

Starting with electricity production and primary energy consumption in the transportation sector, the results of the sensitivities are depicted in Figure 7.7 grouped by sensitivity case. The cases *Carbon price* and *Demand* show the highest effect on electricity production with *Hydrogen* and *Modal shift* being less significant. Naturally, a change of carbon price does not only affect the transportation sector but also all other areas of energy generation directly, which is why the effect on power generation is more pronounced. However, the carbon price does not seem to have nearly as much of an effect on the primary energy consumption in the transportation sector, even though the transformation of the sector towards more electricity and less oil comes with significant reductions of primary energy demand. Here, the effects of *Demand* are the strongest, spanning a wide range of required energy, which is one of the reasons why the sensitivity range for *Demand* was chosen to be smaller compared to the others. The initial increase in primary energy consumption for high demand sensitivities is explained by the increase in demand leading to more energy demand. In the later periods, however, efficiency improvements and electrification dominate the effect of increased demand which leads to the overall reduction of primary energy consumption. A 50% increase in projected transportation demand by 2030 might very well be a too extreme assumption, with the relative changes being more relevant rather than the absolute numbers. Interestingly, *Modal shift* has the second highest effect on primary energy showing that higher shares of public transport can help with reducing the energy demand of the transportation sector.

When taking a look at the emissions (Figure 7.8), a similar picture can be observed. Overall transport related emissions are most affected by *Demand*, followed by *Carbon price* and *Modal shift* with *Hydrogen* having almost no effect at all. The strong reaction to *Demand* can be attributed to the high shares of fossil fuels still prevalent in 2030 and, thus, the additional demand having to be covered by fossil technologies. Another interesting effect is that, while higher (or lower) CO_2 prices lead to less (or more) emissions towards the end of the modeling period, *Modal shift* affects mostly the intermediate years. This can be explained by some modes of transportation (i.e. rail transportation) already being electrified to a high degree and, thus, encouraging a switch from other modes to rail transportation given the possibility. In terms of specific emissions of cars, however, only *Carbon price* shows meaningful deviations compared to the base case, especially when considering lower values (light orange).

Lastly, the electric vehicle stock (cars) and hydrogen production are considered. Figure 7.9 highlights that *Demand*, again, has the highest effect on total number of electric cars, since the number of vehicles is directly correlated to the demand for private road transport. However, *Modal shift* also shows a significant influence on this KPI and highlights that a slight shift towards more public transport can have strong effects on the number of vehicles. A carbon price can change the speed of transition towards electric vehicles in

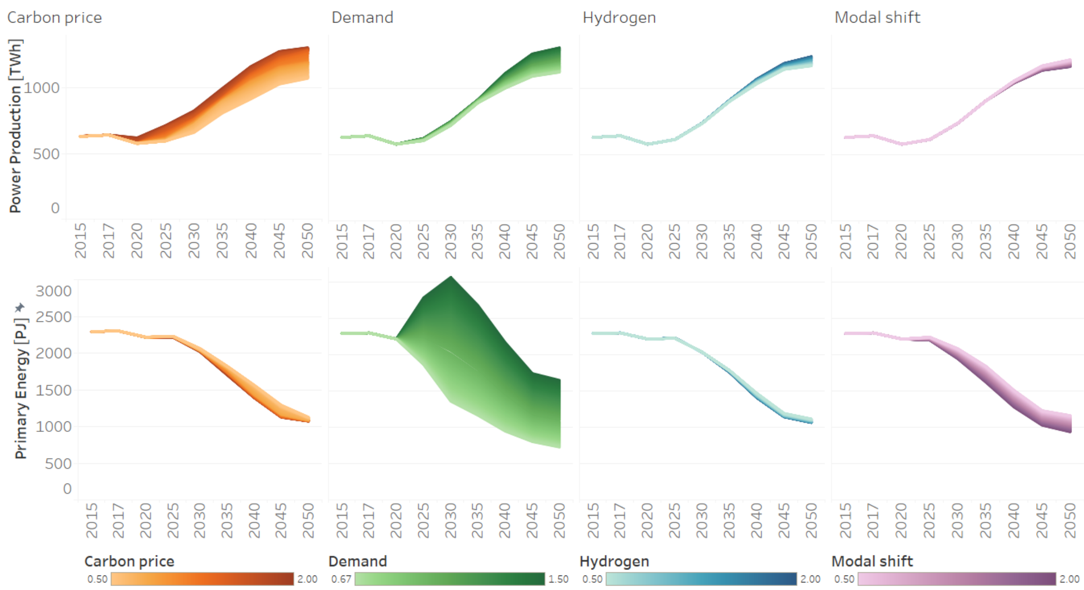

Figure 7.7: Electricity production (top) and primary energy consumption in the transportation sector (bottom) for all sensitivity cases. The color range represents the factor of the respective sensitivity.

the intermediate years, while *Hydrogen* has no deviations at all with both hydrogen and electric vehicles being aggregated for the figure. However, even when separating hydrogen vehicles and BEVs the results show little to no difference suggesting that BEVs are by far superior in terms of energy consumption and economic efficiency. In terms of overall hydrogen production, *Hydrogen* has the highest effect together with *Carbon price* while *Demand* and especially *Modal shift* show less significant results. This suggests that the other energy sectors, especially industry and heating, are more likely to affect hydrogen production, since the two dominant cases not only affect the transportation sector but all sectors. *Demand*, in turn, has much less effect on hydrogen production, even though it showed the strongest effect in most other cases, leading to the conclusion that the role of hydrogen in the transportation sector is quite robust (see Figure 7.6).

7.5.3 Discussion of Model Results and Limitations

The results of the base case describe a pathway which heavily decarbonizes the German energy sector. While some climate targets are achieved (i.e. 80% renewable power generation and 65% GHG emission reduction in 2030), others are missed by a substantial margin like, for example, the 1.5 °C climate target, 15 million electric vehicles in 2030 or reaching

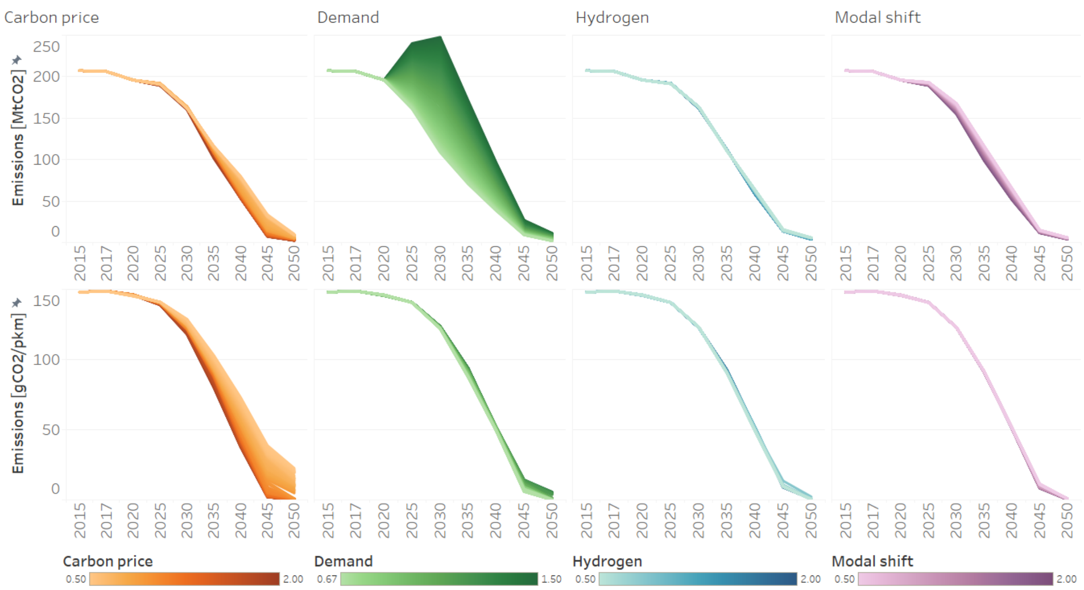

Figure 7.8: Annual transport emissions (top) and specific emissions of cars (bottom) for all sensitivity cases. The color range represents the factor of the respective sensitivity.

climate neutrality by 2045. The national carbon budgets associated with the 1.5 °C or 2 °C climate target, however, can be calculated using different methodologies and the chosen values are on the lower end of the spectrum (Hainsch et al. 2021). Electricity generation needs to be decarbonized quickly to facilitate the electrification of the other energy sectors and, at the same time, expanded significantly in terms of renewable energies to be able to provide the increased demand. New fossil generation capacities are not required which is a result of the integrated optimization recognizing that new investments would quickly become stranded. Shortsighted decision-making, however, can lead to these investments which should be avoided by considering their long-term effects (Löffler et al. 2019). Policy and decision makers should therefore not neglect the long term effects of their decisions which could lead to path dependencies and slow down the speed of transformation.

Similarly to the electricity sector, the transportation sector is quickly transformed towards less carbon intensive technologies in the form of electric vehicles or biofuel based ones where direct electrification is not an option. Rail transportation and public transport prove to be more energy and cost efficient than road transportation coupled with easier electrification. Hydrogen is used significantly in freight transportation, where batteries are not as efficient. The sensitivity analysis highlights that transportation demand has the overall largest effect on most of the considered KPIs, directly affecting primary energy demand, emissions, and

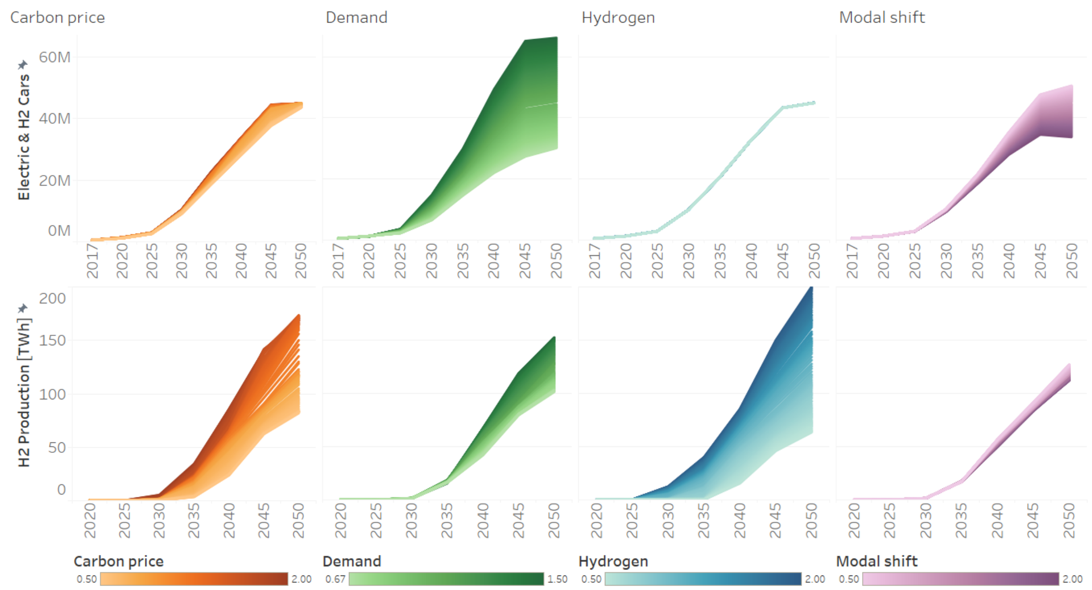

Figure 7.9: Number of electric vehicles (top) and hydrogen production (bottom) for all sensitivity cases. The color range represents the factor of the respective sensitivity.

vehicle stock to a large degree. Policies belonging to the *avoid* category of the A-S-I approach therefore seem to be the most effective tool in achieving the decarbonization of the transportation sector and should be a point of emphasis. Examples could be redesign of streets and blocks to promote non-energetic transportation but also taxes and fees can serve this purpose (GIZ 2019). The *Avoid* category relies significantly on societal support and willingness to adapt which some studies found is present given the correct implementation and communication of measures (Cherry et al. 2018; Schmitz et al. 2019).

A more pronounced modal shift also has a strong effect on number of vehicles, especially when considering that the chosen range of the sensitivity is much lower than of *Demand*. Moreover, focusing on the *Shift* category of A-S-I can help with reducing emissions in the intermediate term, since rail transportation is already mostly electrified. With the electricity sector most likely leading the way in terms of decarbonization, shifting transportation demand from cars to trains can lead to a reduction of emissions even before the large-scale deployment of electric vehicles. The increased electricity demand would be comparably low as illustrated in Figure 7.7.

With respect to carbon prices, the results show relevant results across almost all KPIs. The strongest effects which can be observed on hydrogen production and electricity generation are partially influenced by the effects of a carbon price on the other sectors. Within the transportation sector, the speed of BEV rollout is influenced by higher or lower carbon prices and, as a result, sectoral emissions. The results of the *Carbon price* case can similarly be interpreted for a possible reduction of subsidies for fossil fuels, since both affect fuel costs of vehicles. With the current diesel subsidies of 18.4 cents per liter (UBA 2022), removing the privilege would have roughly the increase in prices as a carbon price increase of 70 €/ton, making this option a simple to execute and precise measure.

Lastly, the *Hydrogen* case has the least impact across all KPIs with only hydrogen production being affected notably. This could lead to two suggestions: On the one hand, the basic assumptions for future development of hydrogen technologies are too pessimistic, such that even a massive improvement in efficiency and costs does not make hydrogen-vehicles the superior option. On the other hand, hydrogen could be limited to specific areas like trucks and buses, as can be seen in the base case in Figure 7.6, being a robust solution for the decarbonization of these areas without many alternatives.

Despite all these findings, some shortcomings of the present analysis and model are important to be mentioned in order to adequately interpret the results. The model takes the perspective of a central planner while in reality, especially in the transportation sector, individuals make decisions which do not align necessarily with climate goals. Particularly important is the modal choice which can not be depicted realistically by the model since, in reality, non techno-economical factors (e.g. weather, time of travel, availability of vehicles) play a significant role. As a result, policies which affect the choice of mode of transportation can not be implemented adequately in the model. With demands being an exogenous parameter, rebound effects of energy efficiency improvements are not considered which is especially important for the *Improve* category of the A-S-I approach. The use of exploratory sensitivity analysis neglects that changing one parameter could have implications on other input parameters. Finally, the linear nature of the model requires simplifications of interactions in order to be computationally feasible.

7.6 Conclusions and Policy Implications

This article analyzes the effect and leverage of specific areas policy and decision makers can target on the overall energy and transportation sector transformation. With the European and German transportation sector being the only energy sector where GHG emissions are still around 1990 levels, policy makers need to define the framework to effectively and rapidly reduce emissions. At the same time, interactions with the entire energy system need to be kept in mind which becomes increasingly complex due to sector coupling and electrification.

The open source Global Energy System Model (GENeSYS-MOD) is used for the analysis. A base scenario is calculated showcasing a possible pathway for the German low-carbon energy system transformation until 2050. With increasing amounts of renewable energy sources and replacement of fossil technologies by cleaner ones, GHG emissions can effectively be reduced. The future transportation sector is dominated by electric vehicles wherever economically feasible, while large parts of freight transportation rely on a combination of hydrogen and biofuels.

A calculation of 400 sensitivities which deviate from the base case reveal that some areas have stronger effects on the future energy and transportation sector than others. A reduction of transportation demand strongly influences the amount of primary energy, emissions, and fleet size while also affecting electricity generation and hydrogen production in meaningful ways. Therefore, focusing on policies which eliminate the need for transportation, e.g. integrating land use and transport planning, traffic management measures, or physically restraining areas by, for example, introducing pedestrian zones (Barcik and Bylinko 2018).

Modal shift suggests to be another effective way of impacting primary energy consumption and fleet size. Moreover, shifting transportation from road to rail, specifically, can lead to significant emission reductions in early years. Rail transportation is already electrified to a large degree which coupled with renewable electricity can reduce transport emissions before large scale deployment of electric vehicles. Incentivizing this shift should be another priority for policy makers by making public transport and long-distance trains more attractive or facilitating multi-modal transportation. Approaches like the recently introduced "9€-Ticket" showed a significant increase in the use rail transportation but also highlighted the need for substantial investments into infrastructure in order to accommodate rising numbers of passengers (Tagesschau 2022). Carbon and road pricing could have similar effects of shifting transportation but also low-emission zones or speed restrictions could serve that purpose (Barcik and Bylinko 2018).

Significant effects can also be observed if carbon prices are altered. Especially emissions, electricity, and hydrogen production react sensitive towards a change in carbon prices. However, this can also be attributed to effects in other energy sectors, as a higher carbon price also applies to the industry and buildings sector. Nevertheless, carbon prices and also the reduction of fossil fuel subsidies are a suitable tool to accelerate the shift towards electrified transportation. Changes in hydrogen costs and efficiencies, on the other hand, show little impact in the transportation sector which suggests a robust role of hydrogen in freight transportation but little to no application for private motorized transport.

This article has highlighted which areas policy makers should target in order to set the framework for a rapid decarbonization of the transportation sector. Transport related emissions need to be reduced quickly if climate goals are to be achieved and this work showcases that high shares of renewable energies and electrification of transportation are major pillars in achieving said goals. Policies which address the areas of avoiding transportation demand or shifting it to less energy intensive and more sustainable modes could have a strong impact on the overall success.

Data availability

The data used for the analysis can be found in Hainsch (2022). The repository contains all relevant input data, model code, and result analyses tools which were used for this work.

Part III

APPENDICES FOR INDIVIDUAL CHAPTERS

Appendix A

Appendix to Chapter 1: Introduction

Table A.1: Further publications with GENeSYS-MOD

Year	Publication
2022	S. Candas et al. 2022b. „Code exposed: Review of five open-source frameworks for modeling renewable energy systems.“ *Renewable and Sustainable Energy Reviews* 161:112272. https://doi.org/10.1016/j.rser.2022.112272
2022	S. Berendes et al. 2022. „Evaluating the usability of open source frameworks in energy system modelling.“ *Renewable and Sustainable Energy Reviews* 159:112174. https://doi.org/10.1016/j.rser.2022.112174
2021	K. Hainsch et al. 2021. „Emission Pathways Towards a Low-Carbon Energy System for Europe: A Model-Based Analysis of Decarbonization Scenarios.“ *The Energy Journal* 42 (01). https://doi.org/10.5547/01956574.42.5.khai
2020	K. Hainsch, L. Göke, et al. 2020. „European Green Deal: Mit ambitionierten Klimaschutzzielen und erneuerbaren Energien aus der Wirtschaftskrise.“ *DIW Wochenbericht* 28:499–506. https://doi.org/10.18723/DIW_WB:2020-28-1
2020	K. Hainsch, H. Brauers, et al. 2020. *Make the European Green Deal Real - Combining Climate Neutrality and Economic Recovery.* Technical report No. 153. Berlin: German Institute for Economic Research (DIW Berlin)
2020	H. Auer et al. 2020. „Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5 °C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE.“ *e & i Elektrotechnik und Informationstechnik* 137 (7): 346–358. https://doi.org/10.1007/s00502-020-00832-7
2019	P.-Y. Oei et al. 2019. „Neues Klima für Europa: Klimaschutzziele für 2030 sollten angehoben werden.“ *DIW Wochenbericht* 2019 (41): 754–760
2018	K. Löffler et al. 2018. „Modeling the Low-Carbon Transformation in Europe: Developing Paths for the European Energy System Until 2050.“ In *Energiewende "Made in Germany",* edited by C. von Hirschhausen et al., 345–374. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-95126-3_13
2018	T. Burandt, K. Löffler, and K. Hainsch. 2018. „GENeSYS-MOD v2.0 - Enhancing the Global Energy System Model.“ *DIW Data Documentation* 94
2018	D. Huppmann et al. 2018. „IAMC 1.5 C Scenario Explorer and Data hosted by IIASA.“ *Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis* 10
2017	C. Kemfert et al. 2017. „Nuclear Power Unnecessary for Climate Protection —There Are More Cost-Efficient Alternatives.“ *DIW Economic Bulletin* 7 (48)
2017	K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert, et al. 2017. „Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS).“ *Energies* 10 (10): 1468. https://doi.org/10.3390/en10101468
2017	K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, and C. von Hirschhausen. 2017. „Decarbonizing the Indian Energy System until 2050: An Application of the Open Source Energy Modeling System OSeMOSYS.“ *IAEE Energy Forum,* Energy Forum, 2017 (Singapore Issue): 51–52
2017	T. Burandt et al. 2017. „Designing a Global Energy System based on 100% Renewables for 2050.“ In *10. Internationale Energiewirtschaftstagung "Klimaziele 2050: Chance für einen Paradigmenwechsel?",* 30. Vienna, Austria

Appendix B

Appendix to Chapter 3: Review and comparison of European energy transition scenarios

B.1 Description of the four openENTRANCE pathways

Directed Transition

In this storyline, as a result of an indifferent public attitude and lacking societal commitment, a strong and continuous incentive-based policy push (at least in Europe) is necessary to deploy existing and novel technologies in the energy and transport sectors. At both European and country levels, active and aligned policy support is necessary to optimally exploit several potentials and available synergies. In a challenging global and European market environment industry is gaining confidence in continuous technology-specific public policy support and takes responsibility to deliver low-carbon mitigating technology portfolios in the absence of significant active societal contributions.

As for the implementation of this storyline into GENeSYS-MOD, the demand for all sectors is slightly lowered due to policy incentives for demand reduction. While this effect is not significant in most sectors, the residential heating demand sees a higher decrease in demand due to a constant process of building modernization and therefore reduced heating demand. In the industrial sector, heavy subsidies, which are implemented as decreasing costs of technologies, help in electrifying most of the process heating demand. Especially hydrogen-based solutions meeting energy services, which are already past their initial state of development today, see significant reductions in their associated costs (as a result of significant policy support) and thus considerable market deployment.

In contrast, currently not available technologies, at least from a technical point-of-view, are not being considered by the model (except CCTS technology). Net imports of hydrogen to Europe are not being considered as a result of the global market situation and reliance on energy security, and fossil fuel prices drop due to lowered global demand. CCTS is an option after the initial model periods due to heavy incentives by politics to reduce emissions, especially in the industrial sector.

Societal Commitment

This storyline mainly describes a prudent society, characterized by a sustainable life style and behavioural changes which includes a significant reduction of energy use for delivering energy and transport services, the implementation of a circular (and partly sharing) economy, as well as the exploitation of digitalization potentials to support individual and local service needs (including those of communities). Completely new business models and market solutions will emerge, partly only locally. Significant shares of local self-consumption (individual prosumers, communities of different sizes) of renewable generation (notably PV) characterizes this story. These ambitions and developments will be supported by tailor-made policymaking, not least as a result of lacking breakthrough of novel technologies (except digitalization) in the energy and transport sectors.

Overall, renewable technologies see higher potentials and market penetration than usually, due to their public support and politics focus on removing regulatory barriers. Society is willing to invest into the sustainable transformation of the energy system (with significant contributions of local self-generation at different levels), which is being implemented by adding a penalty on conventional technologies and, thus, promoting renewable solutions. In addition, the sharing nature of society is simulated by decreasing the costs of passenger vehicles and increasing their efficiency. The former characterizes the sharing nature of the society, with car sharing vehicles usually driving more kilometers per year than privately owned ones, while the latter simulates higher occupancy rates in vehicles due to pooling effects.

Regarding the technology landscape, no negative emission technologies are being allowed in this storyline. Moreover, no new nuclear power plant capacities are being considered as an option (not this is the only openENTRANCE scenario of four in total where this assumption is made). Fossil fuel prices drop due to lowered demand but a high carbon price, the highest in all four pathways, offsets this effect. This high carbon price can be explained by a widespread recognition of environmental externalities caused by greenhouse gases and leads to an almost decarbonized energy system by 2040.

Techno-Friendly

This storyline focuses on the promising breakthrough of novel technologies (incl. floating offshore wind, H_2, and CCTS), being rolled out on a large-scale to meet energy and transport service needs. In addition, this storyline is characterised by the positive attitude of society towards large-scale infrastructure projects mitigating the climate challenge. A strong globalized market-pull triggers technology choice and implementation. Active policymaking is pushed into the background. As a consequence of sufficient low-carbon technology availability, energy demand reductions and active demand side participation of consumers/prosumers are less important, but still needed.

A number of technologies is now available for the model to being used. These include CCTS capacities, significant net H_2 imports to Europe, and the inclusion of certain breakthrough technologies like direct air capture (DAC) or trucks powered by an overhead power line. These technologies follow cost and efficiency projections, which usually makes them very unattractive in the current time periods, but opens up their possibility to significantly contribute in the later periods.

Additionally, as the title of the storyline already suggests, optimistic values for cost and efficiency development of technologies under consideration are implemented. Higher technological learnings can be seen for technologies, which are currently in a less mature state of development, showcasing their potential for a breakthrough. Additionally, new capacities can be built at a higher implementation rate between two periods since infrastructure investments and capacity expansions are facilitated through the storyline. A medium to high carbon price is included as is a cross-sectoral and cross-regional ETS. Fossil fuel prices drop due to lowered demand, yet the combination of the carbon price and technology improvements of carbon-free technologies offset this reduction in prices.

Gradual Development

This storyline entails ingredients of ‘a little of each’ of the remaining openENTRANCE storylines and therefore represents an already ambitious reference scenario in openENTRANCE. The uniqueness of this storyline is that it describes the challenging energy transition with an equal part of societal, industry/technology, and policy action. Several of these three dimensions take responsibility and deliver tailor-made contributions to reach the least ambitious climate mitigation target (2°C; remaining storylines envisage 1.5°C). Carbon pricing in this scenario is more conservative compared to the others.

Costs and efficiencies of all technologies are changed slightly to reflect the pathway characteristics, similar to the Techno-Friendly implementation. Yet, the values are less optimistic and improvements happen at a slower rate. Also, novel and not already proven technologies are not integrated (e.g.DAC, overhead trucks, CCTS) and there is no option foreseen to have net imports of hydrogen from regions outside of Europe. Similar to Societal Commitment, this pathway is also characterized by reductions in energy demand of all different sorts. These reductions, however, are less substantial as in Societal Commitment and, additionally, the potential for demand shifting is far more limited.

B.2 Description of the three studies: openENTRANCE, *A clean planet for all*, and LCEO

openENTRANCE

The ambition of the openENTRANCE project is to develop, use and disseminate an open, transparent and integrated modeling platform for assessing low-carbon transition pathways of the European energy and transport system. This fully open platform will be populated with a suite of modeling tools and datasets selected to cover the multiple dimensions of this transition process. This shall facilitate and improve the dialogue between researchers, policy makers and industry when investigating key questions linked to this transition in the next decades, notably as far as the European energy and transport system is concerned.

Naturally, the European economy is not decoupled from the rest of the world. There exists a strong link and trade relationships to other regions outside Europe. Thus it is straightforward that also models and analyses tools are needed in openENTRANCE for calibration, validation and robustness tests when determining the quantitative European portion needed to achieve particular global goals, e.g. like a global warming temperature ceiling benchmark of 1.5°C or 2.0°C. Therefore, the comprehensive ensembles of datasets on existing global pathway curves embedded into the model MESSAGEix-GLOBIOM play a core role in the openENTRANCE modeling and scenario generation exercises to align the empirical foundation of several quantitative scenario and case studies carried out in this project to the status quo of knowledge in the global climate modeling community.

It is important to note, that in the openENTRANCE project from the very beginning a strong focus has been put to support policy and decision making to succeed in decarbonizing the European economy. However, since future developments in the energy and transport system can’t be foreseen exactly, four different storylines have been developed (i.e. narrative descriptions of equally possible energy futures) in the openENTRANCE project. The corresponding quantitative scenario studies presented in this article directly built upon them. It is important to note that the openENTRANCE storyline descriptions are founded on a thorough analysis of already existing global and European pathway and scenario studies as well as a comprehensive review of the existing policy documents at European Commission level complying to the global climate challenges according to the Paris agreement.

A clean Planet for all (European Commission 2018b)

The aim of this long-term strategy is to confirm Europe's commitment to lead in global climate action and to present a vision that can lead to achieving net-zero greenhouse gas emissions by 2050 through a socially-fair transition in a cost-efficient manner. It underlines the opportunities that this transformation offers to European citizens and its economy, whilst identifying challenges ahead. The proposed Strategy does not intend to launch new policies, nor does the European Commission intend to revise 2030 targets. It is meant to set the direction of travel of EU climate and energy policy, and to frame what the EU considers as its long-term contribution to achieving the Paris Agreement temperature objectives in line with UN Sustainable Development Goals, which will further affect a wider set of EU policies. The Strategy opens a thorough debate involving European decision-makers and citizens at large as to how Europe should prepare itself towards a 2050 horizon and the subsequent submission of the European long-term Strategy to the UN Framework Convention on Climate Change by 2020.

The main model suite used for the scenarios presented in this assessment has a successful record of use in the Commission's energy and climate policy impact assessments. It is the same model suite used for the 2020 and 2030 climate and energy policy framework, as well as for the 2011 Commission' s decarbonisation Roadmaps. The model suite has been strongly enhanced over the past years in terms of more granular representation of both energy system and GHG emissions and removals, and the detail of representation of technologies. The model suite covers:

- The entire energy system (energy demand, supply, prices and investments to the future) and all GHG emissions and removals.
- Time horizon: 1990 to 2070 (5-year time steps)
- Geography: individually all EU Member States, EU candidate countries and, where relevant Norway, Switzerland and Bosnia and Herzegovina.
- Impacts: on all energy sectors (PRIMES and its satellite models on biomass and transport), agriculture (CAPRI), forestry and land use (GLOBIOM-G4M), atmospheric dispersion, health and ecosystems (acidification, eutrophication) (GAINS); macro-economy with multiple sectors, employment and social welfare (GEM-E3).

The models are linked with each other in such a way, so as to ensure consistency in the building of scenarios. These inter-linkages are necessary to provide the core of the analysis, which are interdependent energy, transport and GHG emissions trends.

LCEO (Nijs et al. 2018)

The LCEO is an Administrative Arrangement being executed by JRC for RTD, to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Report on Synergies for Clean Energy Technologies
- Annual Report on Future and Emerging Technologies (information is also systematically updated and disseminated on the online FET Database).

Techno-economic modelling results are also made available via dedicated review reports of global energy scenarios and of EU deployment scenarios.

Appendix C

Appendix to Chapter 4: Assessment of the stranded assets problem in Europe through myopic foresight

C.1 Model description

GENeSYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission targets, integration of renewables, and sector-coupling. The model minimizes the objective function, which comprises total system costs (encompassing all costs occurring over the modeled time period) Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Howells et al. 2011a.

The GENeSYS-MOD framework consists of multiple blocks of functionality, that ultimately originate from the OSeMOSYS framework. Figure C.1 shows the underlying block structure of GENeSYS-MOD v2.0, with the additions made in this study (namely the option to compute scenarios with reduced foresight, as well as some additional data for the policy-driven scenario).

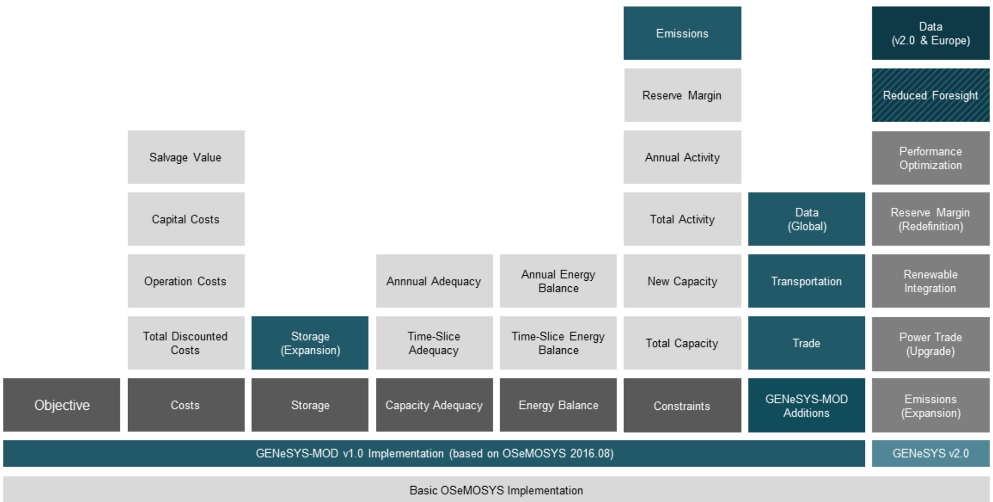

Figure C.1: Model structure of the GENeSYS-MOD implementation used in this study. Source: Own illustration.

(Final) Energy demands and weather time series are given exogenously for each modeled time slice, with the model computing the optimal flows of energy, and resulting needs for capacity additions and storages.[1] Additional demands through sector-coupling are derived endogenously. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g. to limit the usable potential of renewables), RES feed-in (e.g. to ensure grid stability), emission budgets (given either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and yield realistic results.

The GENeSYS-MOD v2.0 model version used in this paper features a total of 16 time slices per year (each quarter of a year with a specific type-day, consisting of four timeslices each). The years 2020-2050 are modeled in 5-year-steps. All input data is consistent with this time resolution. Since GENeSYS-MOD does not feature any stochastic features, all modeled time steps are known to the model at all times. There is no uncertainty about e.g. RES feed-in.

The model allows for investment into all technologies[2] and acts purely economical when computing the resulting pathways (while staying true to the given constraints). It usually assumes the role of a social planner with perfect foresight, optimizing the total welfare through cost minimization. In this paper, an add-on allowing for myopic foresight using multiple computational stages, is introduced. All fiscal units are handled in 2015 terms (with amounts in other years being discounted towards the base year).

Fore more information on the mathematical side of the model, as well as all changes between model versions, please consult Howells et al. 2011a; Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Burandt, Löffler, and Hainsch 2018.

[1] GENeSYS-MOD offers various storage options: Lithium-ion and redox-flow batteries, pumped hydro storages, compressed air electricity storages, gas (hydrogen and methane) storages, and heat storages.

[2] Except when given fixed, predetermined phase-out dates, such as for nuclear in Germany, or coal in Great-Britain. For more information, please consult Burandt, Löffler, and Hainsch 2018.

C.2 Emission budget

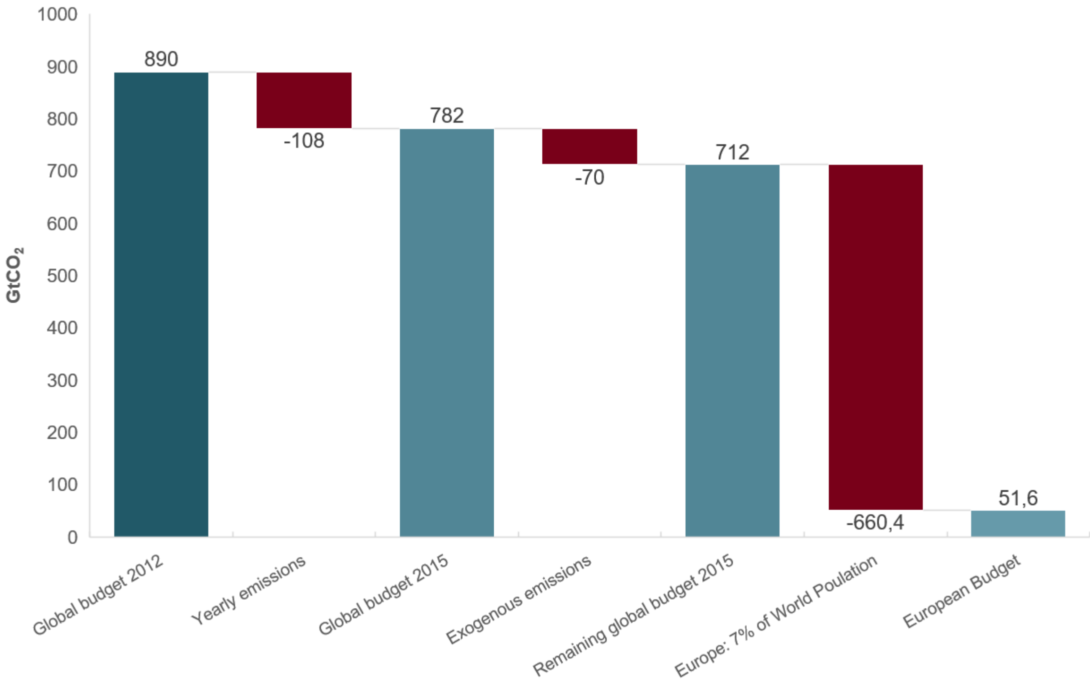

Figure C.2: Emission budget calculations. Source: Own illustration.

C.3 Validation of model results

To validate the model results, the computed values for the base year 2015 have been compared with real-life statistical data to ensure proper functionality of the energy system model. Figure C.3 shows a comparison of model results with historic data for power generation (upper left), emissions per sector (upper right), and primary energy supply (bottom).

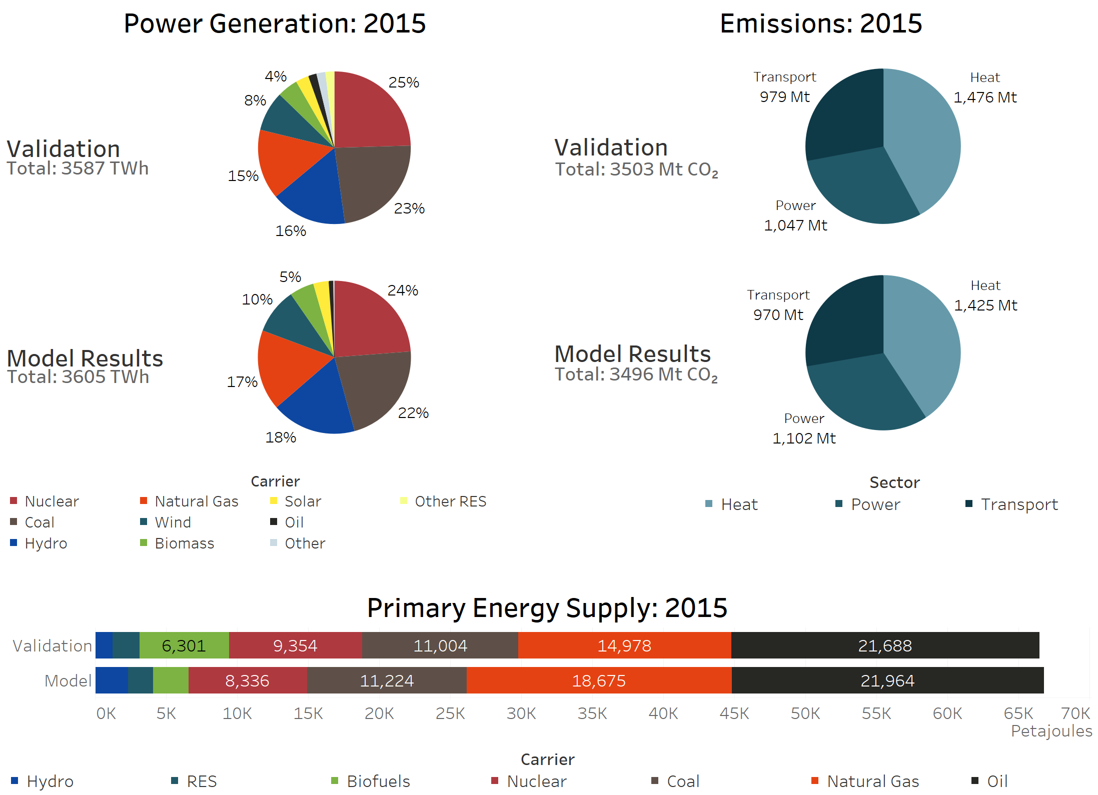

Figure C.3: Comparison of 2015 model results vs. historical numbers. Source: Own calculations, 2015 data based on International Energy Agency 2018a; Statistical Office of the Republic of Serbia 2017; Statistics Norway 2017; Swissgrid 2015; International Energy Agency 2018b; OECD 2017.

Results show that the model numbers are reasonably close to real-life values, usually only diverting less than 1% from historic values (0.5% for total power generated, 0.2% for total emissions, 0.8% for primary energy supply). While there are a few differences between energy carriers and technologies, this usually stems from existing overcapacities in Europe, where the model is able to perform some ”optimization” towards later periods, given the perfect foresight character. We can see that in the power sector, renewables are a bit over-represented (hydro with 18% vs. 16%, wind with 10% vs. 8%, etc.) and fossils a bit under-represented (nuclear with 24% vs. 25%, coal with 22% vs 23%, etc.), except natural gas, which makes up for 17% of the power sector instead of real-life 15%. Albeit their existence, all these differences are small enough to be considered very close to real-life numbers.

The largest difference in numbers lies in the primary energy supply, where natural gas makes up a significantly higher share in the model, while biomass/biofuels see less utilization. This difference mainly comes from the heating sector, where biomass sees less utilization than in historic 2015. A possible explanation for that is the fact that we, in the model, only include second and third generation biofuels, meaning that non-sustainable biomass products are disregarded, driving up the costs for the biomass value-chain. In the end, though, these differences end up in a very similar total primary energy supply.

Also, sensitivity analyses have been conducted to ensure proper functionality and behavior of the model. All tests showed a predicted and/or explainable behavior of the model.

C.4 Model data

This section of the Appendix displays the key financial and technical assumptions that have been used for this study. Fore a more detailed description of all relevant input data, please refer to Burandt, Löffler, and Hainsch (2018).

Regional potentials for utility-scale solar PV, onshore wind, and offshore wind in GW.

	Solar PV	Wind Onshore	Wind Offshore	Total
Austria	29.2	45.8	0	75.0
Balkan States	146.0	237.6	64.5	448.1
Baltic States	41.6	81.8	108.2	231.6
Belgium & Luxemburg	22.8	19.4	9.1	51.3
Czech Republic	38.3	56.1	0	94.4
Denmark	22.5	32.6	149.0	204.1
Europe East	173.8	278.4	24.3	476.5
France	251.8	381.7	133.7	767.2
Germany	200.4	222.6	83.6	506.6
Greece	62.8	105.6	27.6	196.0
Iberia	256.7	417.9	71.7	746.3
Italy	159.9	190.2	77.7	427.8
Netherlands	31.8	23.6	57.1	112.5
Poland	134.4	193.9	40.7	369.0
Scandinavia	62.3	197.4	420.4	680.1
Switzerland	18.7	20.8	0	39.5
United Kingdom	212.2	268.8	364.6	845.6
Total	1865.2	2774.2	1632.2	6271.6

Table C.1: Regional potentials for utility-scale solar PV, onshore wind, and offshore wind in GW. Source: Gerbaulet and Lorenz (2017).

Capital cost of power generation and transformation technologies in €/kW

	2015	2020	2025	2030	2035	2040	2045	2050
Renewables								
PV Utility	1000	580	466	390	337	300	270	246
PV Rooftop [commercial]	1360	907	737	623	542	484	437	397
PV Rooftop [residential]	1360	1169	966	826	725	650	589	537
CSP	3514	3188	2964	2740	2506	2374	2145	2028
Onshore Wind	1250	1150	1060	1000	965	940	915	900
Offshore Wind [shallow]	3080	2580	2580	2580	2330	2080	1935	1790
Offshore Wind [transitional]	3470	2880	2730	2580	2480	2380	2330	2280
Offshore Wind [deep]	4760	4720	4345	3970	3720	3470	3370	3270
Hydro [large]	2200	2200	2200	2200	2200	2200	2200	2200
Hydro [small]	4400	4480	4490	4500	4500	4500	4500	4500
Biomass Power Plant	2890	2620	2495	2370	2260	2150	2050	1950
Biomass CHP	3670	3300	3145	2990	2870	2750	2645	2540
Biomass Power Plant + CCTS	4335	3930	3742	3555	3390	3225	3075	2925
Biomass CHP + CCTS	5505	4950	4717	4485	4305	4125	3967	3810
Geothermal	5250	4970	4720	4470	4245	4020	3815	3610
Ocean	9890	5095	4443	3790	3083	2375	2238	2100
Conventional Power Generation								
Gas Power Plant (CCGT)	650	636	621	607	593	579	564	550
Gas CHP (CCGT)	977	977	977	977	977	977	977	977
Oil Power Plant (CCGT)	650	627	604	581	558	535	512	490
Hard coal Power Plant	1600	1600	1600	1600	1600	1600	1600	1600
Hard coal CHP	2030	2030	2030	2030	2030	2030	2030	2030
Lignite Power Plant	1900	1900	1900	1900	1900	1900	1900	1900
Lignite CHP	2030	2030	2030	2030	2030	2030	2030	2030
Nuclear Power Plant	6000	6000	6000	6000	6000	6000	6000	6000
Transformation & Storage								
Electrolyzer	800	685	500	380	340	310	280	260
Methanizer	492	421	310	234	208	190	172	160
Fuel Cell	3570	2680	2380	2080	1975	1870	1805	1740
Li-Ion Battery	490	170	155	140	140	140	140	140
Redox-Flow Battery	1240	810	770	730	520	310	310	310
Compressed-Air Energy Storage	600	600	565	530	520	510	480	450

Table C.2: Capital cost of power generation and transformation technologies in €/kW. Source: Carlsson et al. (2014), Gerbaulet and Lorenz (2017), and Ram et al. (2017).

Variable costs for transformation and storage technologies, in M€/PJ

	2015	2020	2025	2030	2035	2040	2045	2050
Electrolyzer	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Methanizer [synthetic gas]	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Methanizer [biogas]	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Fuel Cell	11.11	6.94	6.67	6.39	5.42	4.44	4.44	4.44
Li-Ion Battery	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Redox-Flow Battery	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Compressed-Air Energy Storage	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33

Table C.3: Variable costs for transformation and storage technologies, in M€/PJ. Source: Carlsson et al. (2014).

Input fuel efficiency for common conventional power plants.

	2015	2020	2025	2030	2035	2040	2045	2050
CCGT (Natural Gas)	58%	60%	61%	62%	62%	62%	63%	63%
CCGT (Oil)	38%	38%	39%	39%	40%	40%	41%	41%
Hard coal	45%	46%	47%	48%	48%	48%	48%	48%
Lignite	42%	45%	46%	47%	47%	47%	47%	47%
Nuclear	37%	37%	38%	38%	40%	42%	42%	42%

Table C.4: Input fuel efficiency for common conventional power plants. Source: Carlsson et al. (2014).

Fuel prices of fossil fuels in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
World Prices								
Hard Coal	1.52	1.54	1.53	1.52	1.44	1.36	1.28	1.20
Lignite	0.72	0.73	0.73	0.72	0.68	0.64	0.61	0.57
Natural Gas	6.63	6.54	7.72	8.91	9.15	9.38	9.62	9.86
Uranium	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Oil	7.12	10.18	11.02	11.86	11.37	10.88	10.39	9.91

Table C.5: Fuel prices of fossil fuels in M€/PJ. Source: International Energy Agency (2016) and Booz & Company (2014).

Yearly electricity demand per region in TWh.

	2015	2020	2025	2030	2035	2040	2045	2050
Austria	70.31	76.9	83.9	75.3	77.6	79.5	78.2	76.09
Balkan States	155.4	171.5	180.1	150.9	152.0	154.0	155.0	156.2
Baltic States	28.6	32.4	36.7	29.2	29.6	30.3	29.8	29.6
Belgium & Luxembourg	98.5	108.0	114.2	114.4	116.7	115.8	111.8	108.8
Czech Republic	63.5	65.1	67.2	82.0	82.1	84.4	85.5	85.2
Denmark	35.7	37.1	39.2	40.0	40.5	40.8	40.8	38.5
Europe East	132.7	146.8	160.2	143.8	147.2	150.0	151.9	154.4
France	502.8	522.3	536.7	562.9	580.8	590.6	581.8	565.3
Germany	543.6	562.2	562.2	611.0	596.1	590.5	582.2	574.4
Great Britain	355.9	353.7	365.3	451.6	458.9	470.6	476.8	468.2
Greece	53.3	56.4	70.8	74.9	76.0	76.28	76.1	74.7
Italy	361.9	375.1	389.7	390.9	404.3	409.7	421.1	432.4
Netherlands	122.9	132.3	142.6	127.4	128.3	131.1	130.9	130.0
Poland	162.1	178.5	205.9	171.4	176.9	181.8	184.5	176.4
Portugal & Spain	335.5	376.1	415.6	418.0	430.3	435.3	450.3	429.1
Scandinavia	377.4	389.3	402.3	346.7	340.1	335.6	333.3	328.3
Switzerland	64.4	69.4	74.7	76.2	78.6	80.5	79.2	77.1
Total	3464	3653	3847	3867	3916	3957	3969	3904

Table C.6: Yearly electricity demand per region in TWh. Source: Gerbaulet and Lorenz (2017).

Appendix D

Appendix to Chapter 6: Chances and barriers for Germany's *Energiewende*

D.1 Model description

GENeSYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission targets, integration of renewables, and sector-coupling. The model minimizes the objective function, which comprises total system costs (encompassing all costs occurring over the modeled time period) Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Howells et al. 2011b.

The GENeSYS-MOD framework consists of multiple blocks of functionality, that ultimately originate from the OSeMOSYS framework. Figure D.1 shows the underlying block structure of GENeSYS-MOD v2.9, with the additions made in the current model version (namely the option to compute variable years instead of the fixed 5-year periods, as well as an employment analysis module, in addition to the regional data set and the inclusion of axis-tracking PV).

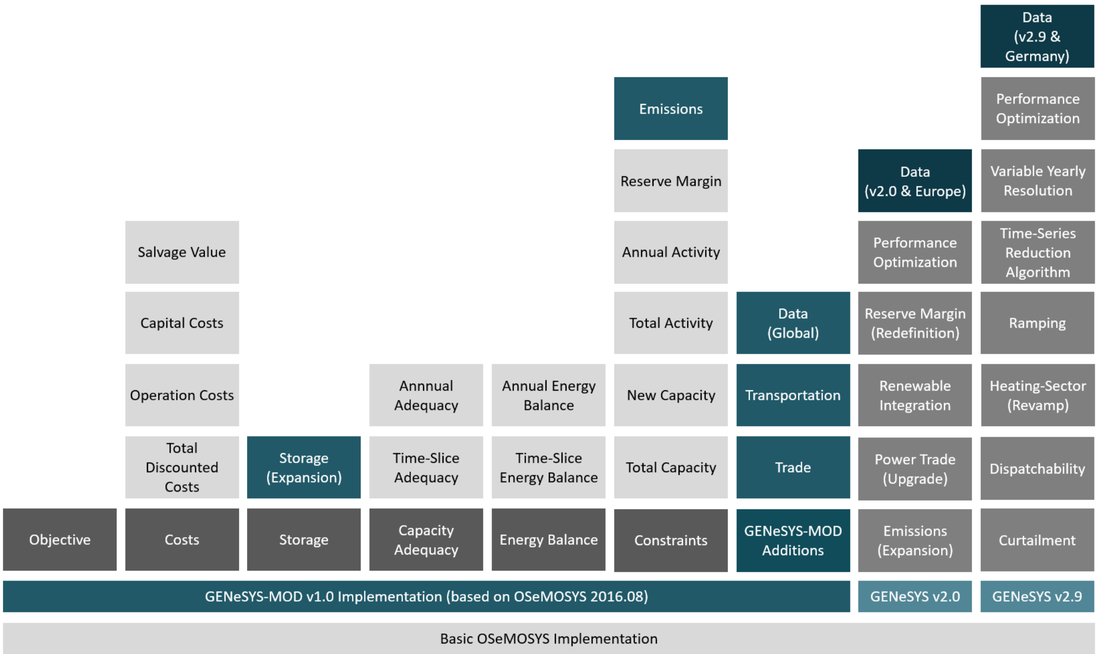

Figure D.1: Model structure of the GENeSYS-MOD implementation used in this study.

(Final) Energy demands and weather time series are given exogenously for each modeled time slice, with the model computing the optimal flows of energy, and resulting needs for capacity additions and storages.[1] Additional demands through sector-coupling are derived endogenously. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g. to limit the usable potential of renewables), RES feed-in (e.g. to ensure grid stability), emission budgets (given either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and yield realistic results.

The GENeSYS-MOD v2.9 model version used in this paper uses the time clustering algorithm described in Gerbaulet and Lorenz (2017) and Burandt et al. (2019), with every 73$^{\text{rd}}$ hour chosen, resulting in 120 time steps per year, representing 6 days with full hourly resolution and yearly characteristics. The years 2017-2050 are modeled in the following sequence: 2017, 2022, 2025, 2030, 2035, 2040, 2045, 2050. All input data is consistent with this time resolution, with all demand and feed-in data being given as full hourly time series. Since GENeSYS-MOD does not feature any stochastic features, all modeled time steps are known to the model at all times. There is no uncertainty about e.g. RES feed-in.

[1] GENeSYS-MOD offers various storage options: Lithium-ion and redox-flow batteries, pumped hydro storages, compressed air electricity storages, gas (hydrogen and methane) storages, and heat storages.

The model allows for investment into all technologies and acts purely economical when computing the resulting pathways (while staying true to the given constraints). It usually assumes the role of a social planner with perfect foresight, optimizing the total welfare through cost minimization. All fiscal units are handled in 2015 terms (with amounts in other years being discounted towards the base year).

For more information on the mathematical side of the model, as well as all changes between model versions, please consult Howells et al. 2011a; Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Burandt, Löffler, and Hainsch 2018; Burandt et al. 2019.

D.2 Selected input data

This section of the Appendix displays the key financial and technical assumptions that have been used for this study. Fore a more detailed description of all relevant input data, please refer to Burandt, Löffler, and Hainsch (2018).

Regional potentials for utility-scale solar PV, onshore wind, and offshore wind in GW.

Region	Solar PV	Wind Offshore	Wind Onshore	Total
BB	27.66	0.00	13.00	40.66
BE	4.08	0.00	0.30	4.38
BW	49.89	0.00	23.00	72.89
BY	81.27	0.00	41.00	122.27
HB	1.27	0.00	0.20	1.47
HE	27.34	0.00	14.00	41.34
HH	2.89	0.00	0.30	3.19
MV	20.05	6.55	11.00	37.60
NI	57.22	49.81	26.00	133.03
NRW	61.44	0.00	20.00	81.44
RP	23.83	0.00	12.00	35.83
SH	19.01	28.64	9.00	56.64
SL	4.36	0.00	2.40	6.76
SN	20.62	0.00	10.00	30.62
ST	19.71	0.00	7.40	27.11
TH	15.77	0.00	7.50	23.27
Total	**436.40**	**85.00**	**197.10**	**718.50**

Table D.1: Regional potentials for utility-scale solar PV, onshore wind, and offshore wind in GW. Source: Bartholdsen et al. (2019).

Capital cost of power generation and transformation technologies in €/kW.

	2015	2020	2025	2030	2035	2040	2045	2050
Renewables								
PV Utility	1000	580	466	390	337	300	270	246
PV Rooftop [commercial]	1360	907	737	623	542	484	437	397
PV Rooftop [residential]	1360	1169	966	826	725	650	589	537
CSP	3514	3188	2964	2740	2506	2374	2145	2028
Onshore Wind	1250	1150	1060	1000	965	940	915	900
Offshore Wind [shallow]	3080	2580	2580	2580	2330	2080	1935	1790
Offshore Wind [transitional]	3470	2880	2730	2580	2480	2380	2330	2280
Offshore Wind [deep]	4760	4720	4345	3970	3720	3470	3370	3270
Hydro [large]	2200	2200	2200	2200	2200	2200	2200	2200
Hydro [small]	4400	4480	4490	4500	4500	4500	4500	4500
Biomass Power Plant	2890	2620	2495	2370	2260	2150	2050	1950
Biomass CHP	3670	3300	3145	2990	2870	2750	2645	2540
Biomass Power Plant + CCTS	4335	3930	3742	3555	3390	3225	3075	2925
Biomass CHP + CCTS	5505	4950	4717	4485	4305	4125	3967	3810
Geothermal	5250	4970	4720	4470	4245	4020	3815	3610
Ocean	9890	5095	4443	3790	3083	2375	2238	2100
Conventional Power Generation								
Gas Power Plant (CCGT)	650	636	621	607	593	579	564	550
Gas CHP (CCGT)	977	977	977	977	977	977	977	977
Oil Power Plant (CCGT)	650	627	604	581	558	535	512	490
Hard coal Power Plant	1600	1600	1600	1600	1600	1600	1600	1600
Hard coal CHP	2030	2030	2030	2030	2030	2030	2030	2030
Lignite Power Plant	1900	1900	1900	1900	1900	1900	1900	1900
Lignite CHP	2030	2030	2030	2030	2030	2030	2030	2030
Nuclear Power Plant	6000	6000	6000	6000	6000	6000	6000	6000
Transformation & Storage								
Electrolyzer	800	685	500	380	340	310	280	260
Methanizer	492	421	310	234	208	190	172	160
Fuel Cell	3570	2680	2380	2080	1975	1870	1805	1740
Li-Ion Battery	490	170	155	140	140	140	140	140
Redox-Flow Battery	1240	810	770	730	520	310	310	310
Compressed-Air Energy Storage	600	600	565	530	520	510	480	450

Table D.2: Capital cost of power generation and transformation technologies in €/kW. Source: Carlsson et al. (2014), Gerbaulet and Lorenz (2017), and Ram et al. (2019).

Variable costs for transformation and storage technologies, in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
Electrolyzer	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Methanizer [synthetic gas]	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
Methanizer [biogas]	1.28	1.28	1.28	1.28	1.28	1.28	1.28	1.28
Fuel Cell	11.11	6.94	6.67	6.39	5.42	4.44	4.44	4.44
Li-Ion Battery	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
Redox-Flow Battery	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56
Compressed-Air Energy Storage	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33

Table D.3: Variable costs for transformation and storage technologies, in M€/PJ. Source: Carlsson et al. (2014).

Input fuel efficiency for common conventional power plants.

	2015	2020	2025	2030	2035	2040	2045	2050
CCGT (Natural Gas)	58%	60%	61%	62%	62%	62%	63%	63%
CCGT (Oil)	38%	38%	39%	39%	40%	40%	41%	41%
Hard coal	45%	46%	47%	48%	48%	48%	48%	48%
Lignite	42%	45%	46%	47%	47%	47%	47%	47%
Nuclear	37%	37%	38%	38%	40%	42%	42%	42%

Table D.4: Input fuel efficiency for common conventional power plants. Source: Carlsson et al. (2014).

Fuel prices of fossil fuels in M€/PJ.

	2015	2020	2025	2030	2035	2040	2045	2050
World Prices								
Hard Coal	1.83	2.02	2.00	1.87	1.83	1.79	1.75	1.71
Lignite	1.36	1.36	1.36	1.36	1.36	1.36	1.36	1.36
Natural Gas	5.97	6.11	6.25	6.45	7.00	7.54	8.09	8.74
Uranium	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Oil	6.99	4.82	7.26	9.64	9.64	9.64	9.64	9.64

Table D.5: Fuel prices of fossil fuels in M€/PJ. Source: World Bank Commodity Price Forecasts 2020.

D.3 German federal states

Table D.6: Acronyms for German federal states.

GENeSYS-MOD	ISO 3166-2:DE	German Federal State
BW	DE-BW	Baden-Württemberg
BY	DE-BY	Bavaria
BE	DE-BE	Berlin
BB	DE-BB	Brandenburg
HB	DE-HB	Bremen
HH	DE-HH	Hamburg
HE	DE-HE	Hesse
MV	DE-MV	Mecklenburg-Vorpommern
NI	DE-NI	Lower Saxony
NRW	DE-NW	North-Rhine-Westfalia
RP	DE-RP	Rhineland-Palatinate
SL	DE-SL	Saarland
SN	DE-SN	Saxony
ST	DE-ST	Saxony-Anhalt
SH	DE-SH	Schleswig-Holstein
TH	DE-TH	Thuringia

D.4 Base case results

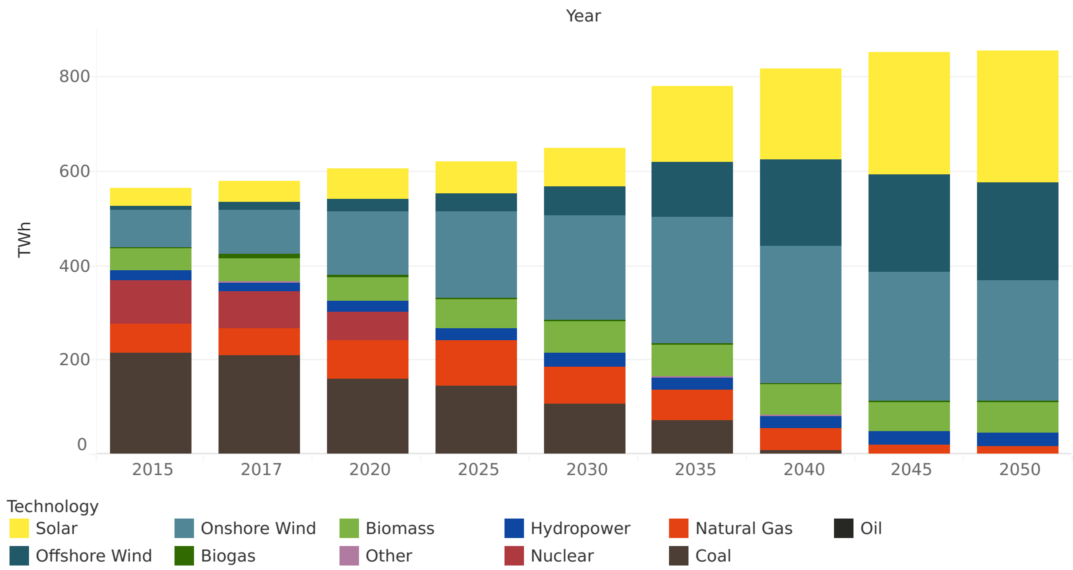

Figure D.2: Power generation per year and technology in the base-case.

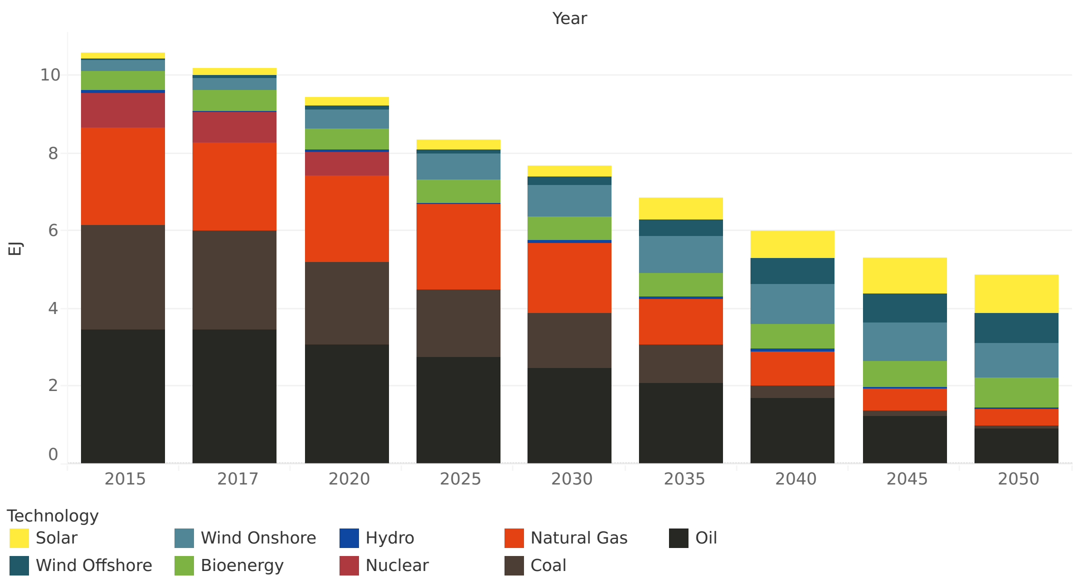

Figure D.3: Primary energy demand per year and fuel in the base-case.

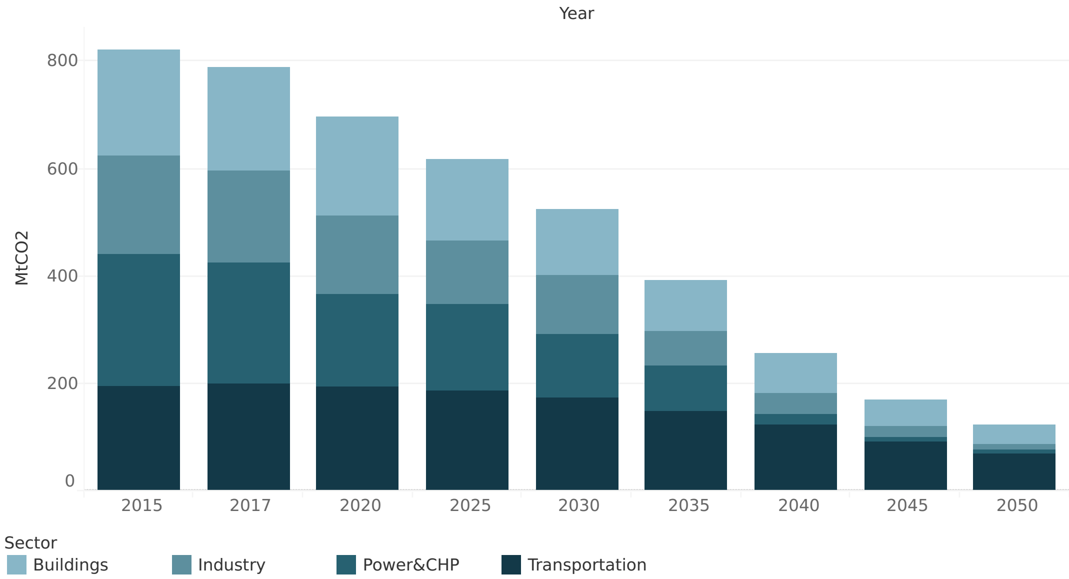

Figure D.4: Emissions per sector and year in the base-case.

D.5 Supplementary material

The supplementary material to this paper, including input data tables and additional results can be found at the Zenodo repository 'GENeSYS-MOD Germany: Technology, demand, and renewable data' (Löffler, Burandt, and Hainsch 2020).

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Übersicht zu in der Dissertation enthaltenen Publikationen

Karlo Hainsch. 2022. European and German low-carbon energy transition - Model-based identification of no-regret options under different types of uncertainty

Chapter	Pre-publications
2	**Lessons from modeling 100% renewable scenarios using GENeSYS-MOD**
	This chapter is based on the article under the same name in *Economics of Energy and Environmental Policy* 9 (1), 2020
	Version: Postprint; DOI: https://doi.org/10.5547/2160-5890.9.1.poei; published open access under CC BY 4.0
3	**Review and comparison of European energy transition scenarios**
	This chapter is based on: "Energy Transition Scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal?", *Energy* (239, Vol. C), 2022
	Version: Postprint; DOI: https://doi.org/10.1016/j.energy.2021.122067; published open access under CC BY 4.0
4	**Assessment of the stranded assets problem in Europe through myopic foresight**
	This chapter is based on: "Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem", *Energy Strategy Reviews* 26, 2019
	Version: Postprint; DOI: https://doi.org/10.1016/j.esr.2019.100422; published open access under CC BY 4.0.
5	**Model comparison on the German energy system transformation**
	This chapter is based on: "Comparing open source power system models - A case study focusing on fundamental modeling parameters for the German energy transition", *Renewable and Sustainable Energy Reviews* 161, 2022
	Version: Postprint; DOI: https://doi.org/10.1016/j.rser.2022.112331; published open access under CC BY 4.0.
6	**Chances and barriers for Germany' s Energiewende**
	This chapter is based on: "Chances and barriers for Germany's low carbon transition - Quantifying uncertainties in key influential factors", *Energy* 239 (Part A), 2022
	Version: Postprint; DOI: https://doi.org/10.1016/j.energy.2021.121901; published open access under CC BY 4.0.
7	**Identifying policy areas for the transition of the transportation sector**
	This chapter is under review in *Energy Policy* using the same title.
	Version: Manuscript version, submitted to journal. Currently in the first revision. Will be published open access.