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# DECARBONIZING THE GLOBAL ENERGY SYSTEM

## MODELING GLOBAL AND REGIONAL TRANSFORMATION PATHWAYS WITH MULTI-SECTOR ENERGY SYSTEM MODELS

vorgelegt von

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to the Faculty VII – Economics and Management
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and

to the Faculty of Economics and Management
at Norwegian University of Science and Technology in Trondheim, Norway

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*All models are wrong, but some are useful*
— George Box, 1976

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# Abstract

This dissertation analyzes the decarbonization of the global energy system with the multi-sectoral energy system model GENeSYS-MOD (Global Energy System Model). The thesis consists of an introductory chapter that introduces the motivation and research questions, as well as the concept of sector coupling and a review of currently available energy system models. This chapter is followed by two parts, analyzing overarching research questions regarding multi-sector energy system models and decarbonization pathways.

Part I introduces GENeSYS-MOD, its ethos, core concepts, and key assumptions and applies the model to a global case study investigating an energy system based on 100% renewables. Results suggest that a reconfiguration of the energy system towards renewable energy sources is possible and required in order to comply with international climate targets. This part further elaborates on the lessons learned from modeling 100% renewable scenarios using GENeSYS-MOD. The primary assumptions and their impact on the feasibility of 100% renewable scenarios are discussed for several configurations of GENeSYS-MOD.

Part II focuses on regional applications with GENeSYS-MOD in conjunction with specific research questions for the analyzed regions. In these regional case studies, the model is not only applied but constantly enhanced and expanded. First, the stranded assets problem in Europe is analyzed with a myopic foresight version of GENeSYS-MOD. The results focus on the amount of stranded capital and the overall negative impact of short-sighted politics in the context of climate change. Second, the effects of climate policies and carbon budgets on the transformation of the Chinese energy system are assessed. Results show that for complying with a 2 °C target, coal consumption needs to be drastically reduced, especially in the power sector. For even more ambitious climate targets (1.5 °C), substantial increases in overall power demand and supply are being observed due to the increased deployment of sector coupling technologies. Third, this part also introduces a stochastic version of GENeSYS-MOD applied to the Japanese energy system, discussing the necessity of hydrogen imports for reaching ambitious decarbonization targets. Hereby, the importance and system-wide benefits of importing hydrogen are highlighted, although the overall system costs only increase slightly without the possibility of hydrogen imports.

This dissertation emphasizes the value of a sector coupled perspective for long-term energy system planning and provides numerous research insights about global and regional decarbonization pathways. With this thesis, I add to the scientific debate and academic literature about the value and importance of multi-sectoral perspectives for energy systems modeling and decarbonization pathways.

**Keywords** Energy system modeling; energy system transformation; techno-economic analysis; bottom-up modeling; sector coupling; multi-sectoral perspective; uncertainty; decarbonization; renewable energy sources; hydrogen; electrification; power-to-X; open source; operations research, Europe; China; Japan

# Zusammenfassung

Diese Dissertation analysiert die Dekarbonisierung des globalen Energiesystems mithilfe des multisektoralen Energiesystemmodells GENeSYS-MOD (Global Energy System Model). Die vorliegende Arbeit besteht aus einem Einführungskapitel, in welchem Motivation, Forschungsfragen und grundlegende Konzepte eingeführt werden. Weiterhin wird ein Überblick über die derzeit verfügbaren Energiesystemmodelle gegeben. Gefolgt wird das Kapitel von zwei Teilen, in denen übergreifende Forschungsfragen zu multisektoralen Energiesystemmodellen und Dekarbonisierungspfaden analysiert werden.

Teil I stellt die Kernkonzepte und Schlüsselannahmen von GENeSYS-MOD vor und wendet das Modell auf eine globale Fallstudie an, die ein Energiesystem auf Basis von 100% erneuerbaren Energien untersucht. Die Ergebnisse zeigen, dass eine Umgestaltung des Energiesystems hin zu erneuerbaren Energiequellen notwendig ist, um die internationalen Klimaziele zu erreichen. In Teil I werden zudem die Erkenntnisse aus der Modellierung von weiteren 100% erneuerbaren Szenarien mit GENeSYS-MOD weiter ausgeführt. Die primären Annahmen und ihre Auswirkungen werden für verschiedene Konfigurationen von GENeSYS-MOD aufgezeigt und diskutiert.

Teil II verlegt den Fokus auf regionale Anwendungen mit GENeSYS-MOD in Verbindung mit spezifischen Forschungsfragen für die jeweils analysierten Regionen. In diesen regionalen Fallstudien wird das Modell nicht nur angewandt, sondern ständig weiterentwickelt. Zunächst wird das Problem der *stranded assets* in Europa mit Hilfe einer myopischen Foresight-Version von GENeSYS-MOD analysiert. Die Ergebnisse zeigen insgesamt negativen Auswirkungen einer kurzsichtigen Politik im Kontext des Klimawandels auf. Zweitens werden in diesem Teil die Auswirkungen von Klimapolitik und $CO_2$-Budgets auf die Transformation des chinesischen Energiesystems untersucht. Die Ergebnisse zeigen, dass für die Einhaltung eines 2 °C-Ziels insbesondere der Kohleverbrauch drastisch reduziert werden muss. Für noch ehrgeizigere Klimaziele (1,5 °C) werden aufgrund des verstärkten Einsatzes von Sektorkopplungstechnologien erhebliche Steigerungen der gesamten Stromnachfrage und -versorgung beobachtet. Drittens wird in diesem Teil auch eine stochastische Version von GENeSYS-MOD auf das japanische Energiesystem angewandt. Hierbei wird die Notwendigkeit von Wasserstoffimporten zur Erreichung ambitionierter Klimaziele diskutiert. Dabei wird die Bedeutung und der systemweite Nutzen des Wasserstoffimports hervorgehoben, obwohl die Gesamtsystemkosten ohne diese Möglichkeit nur geringfügig steigen.

Diese Dissertation unterstreicht den Wert einer sektorgekoppelten Perspektive für die langfristige Energiesystemplanung und liefert zahlreiche Forschungserkenntnisse über globale und regionale Dekarbonisierungspfade. Mit dieser Arbeit steuere ich wesentliche Beiträge zu der wissenschaftlichen Debatte über den Wert und die Bedeutung von multisektoralen Sichtweise für die Modellierung von Energiesystemen und Dekarbonisierungspfaden bei.

**Schlagworte** Energiesystemmodellierung; Energiesystemtransformation; techno-ökonomische Analyse; Bottom-up Modellierung; Sektorenkopplung; multisektorale Perspektive; Unsicherheit; Dekarbonisierung; erneuerbare Energien; Wasserstoff; Elektrifizierung; Power-to-X; Open Source; Operations Research, Europa; China; Japan

# Abstrakt

Denne avhandlingen fokuserer på avkarbonisering av det globale energisystemet med multi-sektor energisystem-modellen GENeSYS-MOD (Global Energy System Model). Avhandlingen består av et introduksjonskapittel etterfulgt av to deler som analyserer overordnede forskningsspørsmål om flersektorielle energysystem-modeller og strategier for avkarbonisering. Det første kapittelet introduserer motivasjonen og forskningsspørsmålene, samt konseptet sektorkobling og en gjennomgang av alternative energisystem-modeller.

Del I introduserer GENeSYS-MOD, dens etos, kjernekonsepter, og nøkkelantakelser, og den presenterer bruk av modellen i en gobal casestudie som undersøker et energisystem basert på 100% fornybare kilder. Resultater viser at en transformasjon av det globale energissytemet mot fornybare kilder er mulig og nødvendig for å overholde internasjonale klimamål. Denne delen utdyper også nyttig lærdom knyttet til modellering av 100% fornybare scenarioer med GENeSYS-MOD. De primære antakelsene og deres implikasjoner for gjennomførbarheten til 100% fornybare scenarioer diskuteres for ulike konfigurasjoner av GENeSYS-MOD.

Del II fokuserer på regionale anvendelser av GENeSYS-MOD for å støtte spesifikke forsknings-spørsmål knyttet til de analyserte regionene. I disse regionale anvendelsene blir ikke modellen bare brukt, men også utvidet og forbedret. Først blir problemet med ikke-utnyttbare resursser (ßtranded assets") analysert for Europa med en versjon av GENeSYS-MOD som tar for seg en kortsiktig investeringshorisont. Resultatene presenterer mengden ikke-utnyttbar kapital og den overordnede negative innvirkningen av kortsiktig klimapolitikk. Videre vurderer denne delen effekten av klimapolitikk og karbonbudsjetter på transformasjonen av det kinesiske energisysemet. Resultater viser at kullforbruk, særlig i kraftsystemet, må reduseres kraftig for å nå 2 °C-målet. For enda mer ambisiøse klimamål (1.5 °C) observeres en omstendig økning i helhetlig kraftforsyning og kraftetterspørsel grunnet økt bruk av teknologi som kobler sektorer sammen. Til slutt introduserer denne delen en stokastisk versjon av GENeSYS-MOD som anvendes på det japanske energisystemet, og nødvendigheten for import av hydrogen for å nå ambisiøse klimamål diskuteres. Her fremheves viktigheten og helhetlig systemnytte av hydrogenimport, til tross for at muligheten for hydrogenimport bare gir en begrenset reduksjon av totale systemkostnader.

Denne avhandlingen fremhever verdien av et sektorintegrert perspektiv ved langsiktig planlegging av energisystemer og gir flere forskningsinnsikter knyttet til globale og regionale strategier for avkarbonisering. Gjennom denne avhandlingen bidrar jeg til den vitenskapelige debatten og den akademiske litteraturen som omhandler verdien og viktigheten av flersektorielle perspektiver i energisystemmodellering og strategier for avkarbonisering.

**Nøkkelord** : Energsystem-modellering; energisystemtransformasjon; teknisk-økonomisk analyse; bottom-up modellering; sektorkobling; flersektorelt perspektiv; usikkerhet; avkarbonisering; fornybare energikilder; hydrogen; elektrifisering; power-to-X; åpen kildekode; Operations Research, Europa; Kina; Japan

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Thank you all for everything!
Danke für alles!
Takk for alt!

# Overview

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# List of Abbreviations

| | |
|---|---|
| C | celsius |
| CCS | carbon capture and storage |
| CCTS | carbon capture, transport, and storage |
| CGE | computable general equilibrium |
| CHP | combined heat and power |
| $CO_2$ | carbon dioxide |
| CSP | concentrated solar power |
| DAC | direct air capture |
| DC | direct current |
| DESSTinEE | Demand for Energy Services, Supply and Transmission in EuropE |
| EJ | exajoule |
| EU | European Union |
| FCEV | fuel-cell electric vehicle |
| FYP | five-year plan |
| GAMS | General Algebraic Modeling System |
| GDP | gross domestic product |
| GEM-E3 | General Equilibrium Model for Economy-Energy-Environment |
| GENeSYS-MOD | Global Energy System Model |
| GHG | Greenhouse gas |
| GMPL | GNU Mathematical Programming Language |

| | |
|---|---|
| Gpkm | giga passenger-kilometers |
| Gt | gigaton |
| Gtkm | giga tonne-kilometers |
| GW | gigawatt |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| km | kilometers |
| kWh | kilowatt hour |
| LEAP | Long-Range Energy Alternatives Planning Model |
| LUT | Lappeenranta University of Technology |
| MGA | Modeling to Generate Alternatives |
| MIT-EPPA | MIT Emissions Prediction and Policy Analysis |
| NDC | nationally determined contribution |
| NET | negative emission technology |
| O&M | operation and maintenance |
| OECD | Organization for Economic Co-operation and Development |
| oemof | Open Energy Modelling Framework |
| PJ | petajoule |
| POL | political boundaries scenario |
| PRIMES | Price-Induced Market Equilibrium System |

| | |
|---|---|
| PV | photovoltaics |
| PyPSA | Python for Power System Analysis |
| RED | reduced foresight scenario |
| REMix | Renewable Energy Mix |
| RES | renewable energy sources |
| Temoa | Tools for Energy Model Optimization and Analysis |
| TIMES | The Integrated MARKAL-EFOM System |
| TWh | terawatt hour |
| UBA | German Environment Agency |
| UN | United Nations |
| WEM | World Energy Model |
| WEO | World Energy Outlook |

# Chapter 1

# Introduction

## 1.1 Motivation and research questions

Since the beginning of my Bachelor's studies, I have developed a keen interest in investigating economic, ecologic, and political questions with the help of quantitative models. Especially in 2013 when I took the lecture *Operation Research - Methods for Network Engineering*, I learned the basic concepts of modeling different types of energy and commodity flows in various sectors. However, most of these concepts were taught as separate concepts with limited or no interaction between them. As an engineer by training, I was eager to combine the aforementioned concepts and to look at holistic analyses. Thus, I developed a model to analyze the food-water-energy nexus and the optimal allocation of scarce water resources in the Aral Sea Basin in my Bachelor's thesis. In this regard, not only the economic aspect of welfare optimization but also the need for sustainable water usage was of relevance. In 2016, I took part in the study research project *Operations Research - Methods for Engineering and Resource Markets* aiming to further look into quantitative modeling. In this study project, we used an open-source energy modeling framework to analyze the possibility of 100% renewables in the global energy system, not only in the power sector but in heating and transportation, too. This analysis was a cornerstone for this dissertation, as the modeling work utilized in the study project was then continued afterwards which culminated in my first scientific publication: *Designing a Model for the Global Energy System – GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)* (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017). This publication is now part of this dissertation as presented in Chapter 2.

However, when I first presented this work at the 10. Internationale Energiewirtschaftstagung (International Energy Business Conference) in Vienna in 2017, the research was received with mixed feelings. First, many researchers rejected the need for 100% renewable power systems to comply with Paris Agreement targets. In general, the acceptance of 100% renewable scenarios was very low, although the Paris Agreement was then already two years in place. This resulted from the power-system only perspective many researchers had at this conference and the lack of awareness that non-electricity sectors have different decarbonization needs. There are cross-sectoral effects when using a holistic perspective in energy systems modeling. When only considering the power sector, the steps needed to comply with the Paris Agreement are different in power system only analyses than multi-sectoral assessments. Second, most questions asked by the audience in general only focused on power sector specific topics, basically ignoring large parts of the actual presentation, results, and key insights. Lastly, the results were interpreted as *forecasts* by parts of the audience. However, as energy system models are always data and assumption-driven, they should never be used for long-term forecasts and instead should be used to generate insights about the changes that *need to happen* to reach certain goals.

Combining this experience with my own belief of the importance of sector coupling in future energy systems, I started this dissertation entitled: *Decarbonizing the Global Energy System*. The title of my thesis represents the three key elements I wanted to focus on:

**Decarbonizing** The political urgency of reducing greenhouse gas emissions is widely accepted, as a global mean temperature rise of more than 2 °C above pre-industrial levels would lead to severe environmental and economic costs for society (Stern 2007). The single most important global agreement for limiting the global mean temperature increase to well below 2 °C is given by the Paris Agreement (UNFCCC 2015).

**Global** Generally with the adoption of the Paris Agreement, the *global* community acknowledged the global relevance of *global* warming and climate change. The transformation of the energy system towards renewable and sustainable energy supply is not only a regional problem but requires international, intercontinental, and even global perspectives.

**Energy System** For a successful decarbonization and to comply with the targets of the Paris Agreement, traditional single sectoral (e.g., power sector) perspectives are no longer sufficient for assessing the necessities of energy transformation pathways. Instead multi-sectoral and holistic analyses are required, as they contain feedback loops and are able to generate more holistic results (Fridgen et al. 2020).

Considering these aforementioned elements, this dissertation focuses on the following key research questions:

1. What are the general properties of largely decarbonized energy systems? What role play regional differences in energy transformation pathways?
2. What impacts for future energy systems arise from coupling the power sector with non-electricity sectors? What will be the main energy carriers and technologies utilized in sector coupled energy systems?

The remainder of this chapter continues with an introduction into the global climate policy background. The next section focuses on the concept of sector coupling, also presenting some key technologies utilized within this concept. A broader categorization of energy system models is presented afterwards, also containing an in-depth review of current bottom-up energy system models investigating multi-sectoral coverage and sector coupling aspects. A detailed outline of the dissertation is given in Section 1.5, followed by key conclusions and an outlook for further research.

## 1.2 Climate policy context

The effect of $CO_2$ on the global mean temperature has been first discovered by Arrhenius (1896). In his calculations, he presented the correlation of atmospheric $CO_2$ content and global atmospheric temperature levels, thus showing that $CO_2$ acts as a greenhouse gas. Overall, he estimated through multiple calculations that a global mean temperature increase of 4-6 °C is possible if the carbon content of the atmosphere would double. Those calculations were used by Manabe and Wetherald (1967) in a more sophisticated version. They concluded that a doubling of carbon dioxide would still result in a global mean temperature increase of approximately 2 °C compared to pre-industrial levels. Eventually, approximately 100 years after Arrhenius' discovery, the relationship between $CO_2$ as a greenhouse gas and the global atmospheric temperature was empirically confirmed, when Lorius et al. (1985) analyzed drilled ice cores from Antarctica. Following this, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988 with the goal of providing regular assessments of climate change for policy and decision makers. The IPCC set the scientific framework for the first conference of the parties in 1995, which laid the groundwork for the first worldwide greenhouse gas reduction treaty: the Kyoto Protocol (UNFCCC 1997).

As presented by Stern (2007), a global mean temperature rise of more than 2 °C above pre-industrial levels would lead to severe environmental and economic costs for society and thus, the emission of greenhouse gases (especially $CO_2$ as the main contributor) should be drastically reduced. The higher the increase of the global mean temperature is, the higher will be the degree of additional risk due to climate change. The future risks can be categorized into different groups: The first category consists of unique and threatened system, which at a warming of 2 °C are at very high risk, particular ice systems in the Arctic Sea and coral reefs. Secondly, extreme weather events need to be listed, which are moderate at recent temperatures and high at a warming around 1 °C. These imply heat waves, extreme precipitation, and coastal flooding. Moreover, the distribution of impacts plays a significant role, which is generally greatest in less-developed areas and risks become high for warming above 2 °C in the global south. Fourthly, also global aggregate impacts need to be taken into account, which include risks for the global economy and earth´s biodiversity. These risks are still moderate after warming between 1-2 °C but become high around 3 °C. Last but not least, large-scale singular events can also be an effect of climate change, which means that some physical systems or ecosystems may be at risk of irreversible drastic change.

In this regard, the IPCC calculated a global carbon budget. They concluded that there is a remaining budget of 870-1240 $GtCO_2$ that can be emitted between 2011 and 2050 to have a more than 50% chance of keeping the global warming below 2 °C.[1] The next step for the global community to accept the relevance of climate change happened with the adoption of the sustainable development goals in which climate action was redeemed one of the goals (United Nations 2015). In the same year, the global community agreed to keep the global mean temperature well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels (Paris Agreement (UNFCCC 2015)). The Paris Agreement is the first legally binding international treaty on climate change. The member countries of the United Nations need to submit their plans for climate action known as nationally determined contributions (NDCs). With these, the countries communicate actions they will take to reduce their greenhouse gas emissions in order to reach the goals of the Paris Agreement. After their initial submissions, the countries are obliged to update their NDCs every 5 years.[2]

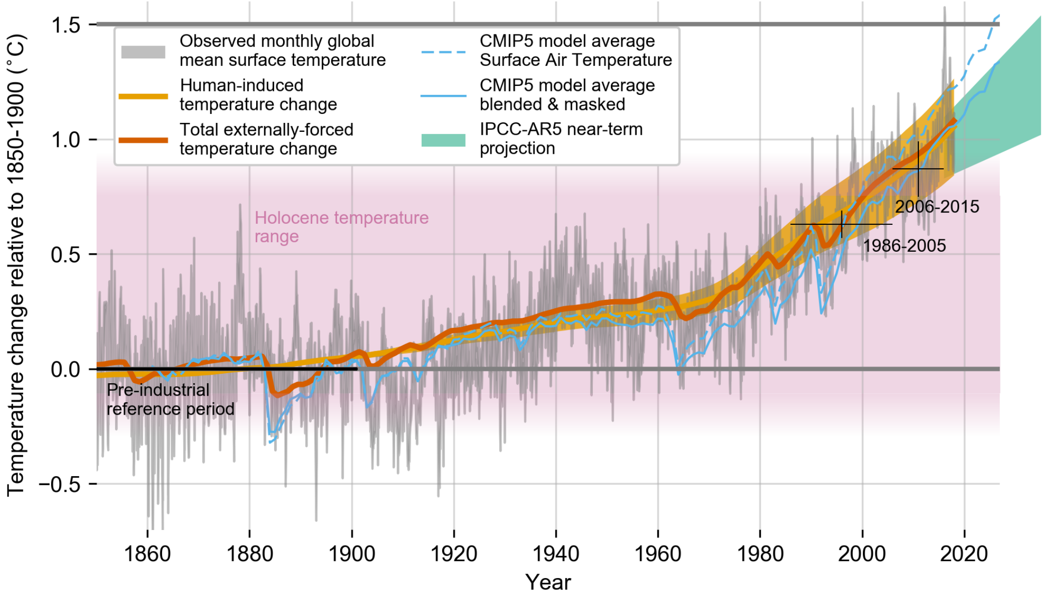

Figure 1.1: Evolution of global mean surface temperature over the period of instrumental observations. Figure taken from IPCC (2018).

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[1] These estimates are based on several uncertainties that can severely impact resulting carbon budgets. Thus, actual global budgets may be higher or even lower (Rogelj et al. 2019).

[2] The NDCs have been updated in September 2020.

As depicted by Figure 1.1, current global temperature levels are already increased by around 1 °C compared to pre-industrial levels. Thus, the recent IPCC Special Report on 1.5 °C (IPCC 2018) highlights that even more ambitious and immediate actions compared to the currently in place policies are needed in order to keep the global mean temperate below 1.5 °C.

Climate Action Tracker (2020) analyzed the 2020 updated NDCs with their compliance to the Paris Agreement and the ambitious to keep the global mean temperature increase to well below 2 °C.

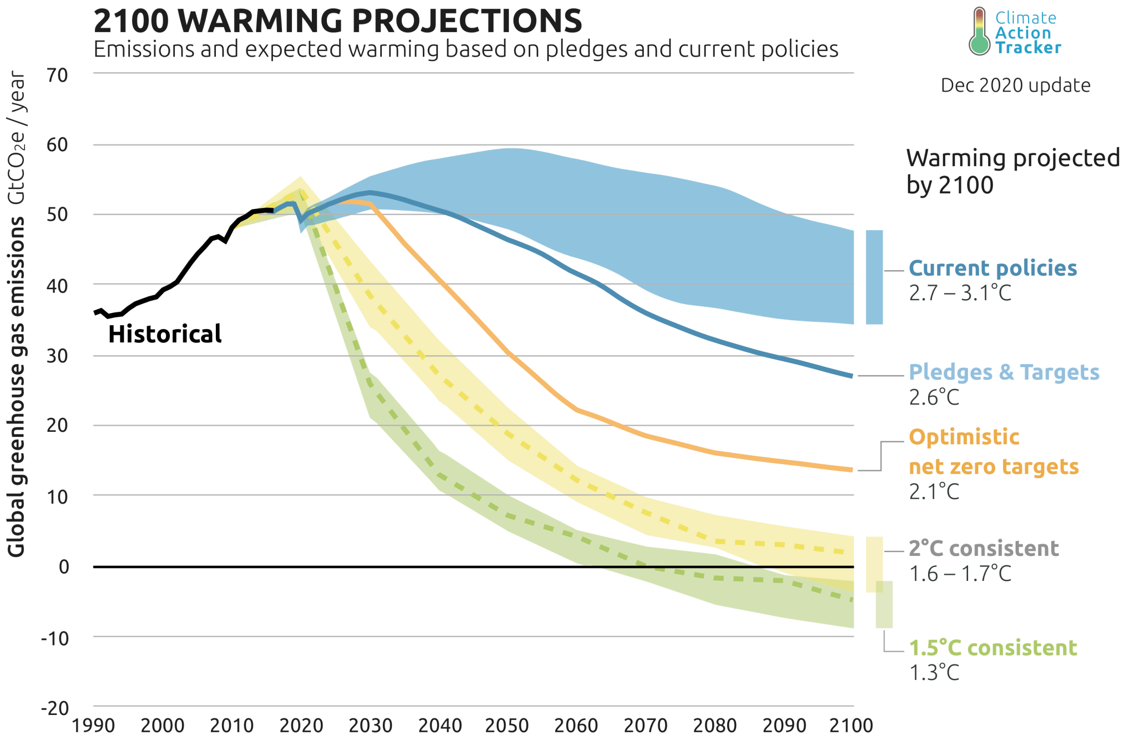

Figure 1.2: Global greenhouse gas emission pathways for different estimates of current policies, current pledges, and targets. Figure taken from Climate Action Tracker (2020).

As presented in Figure 1.2, current policies still have a trajectory that will finally lead to a global mean temperature increase of 2.7-3.1 °C. Even if the current NDCs are being upheld, this would still result in a global warming of about 2.6 °C. Even with the dip in emissions due to COVID-19 pandemic in 2020, it is assumed that the global greenhouse gas emissions continue rising until 2030. Instead global $CO_2$emissions would have to be cut in half by

2030 to be in line with trajectories compatible with the 1.5°C limit (Climate Action Tracker 2020). In light of this, the current climate and energy policies of the regions targeted in this Dissertation are shortly presented in the following subsections.

### 1.2.1 European energy and climate policy

Initially, to be in line with In line with this, the European Union has committed to binding targets for a renewable energy share of at least 32% by 2030 (EC 2018/201) along with greenhouse gas emission reductions of at least 40 % by 2030 compared to 1990 (EC 2018/8422). In December 2019, the European Commission increased the existing climate ambitions by presenting their plans for tackling climate and environmental-related challenges. This plan - the European Green Deal - ”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 2019). As presented by Climate Action Tracker (2020), this pledge for carbon neutrality and commitment to the Paris Agreement by the European Commission is necessary to be uphold in order to limit the global warming to 1.5°C.

### 1.2.2 Chinese energy and climate policy

To comply with the Paris Agreement, China has underlined its ambition within its NDCs to set an end to the ever-rising consumption of coal, with an expected peak around 2030 (Wei 2015). Among other goals, China especially targets to decrease its carbon intensity by 60-65% compared to 2005. In 2020, China has strengthened their initial NDC targets. These updated NDCs, i.a., aim to decrease the carbon intensity by over 65% and to increase the installed capacity of wind and solar power to 1200 GW by 2030. Still, Climate Action Tracker (2020) rates these targets as ”highly insufficient” for complying to the Paris Agreement. Additionally to its NDCs, President Xi Jinping announced in September 2019 that China would aim for a ”carbon neutrality” target ”before 2060”.

### 1.2.3 Japanese energy and climate policy

In this regard, Japan also handed in their Nationally Determined Contributions (NDCs). These aim for an emission reduction of 15 % until 2030 compared to 2019 levels (Ministry of the Environment 2016). Japan’s NDCs have been also updated in 2030 and additionally aim for a greenhouse gas reduction of 80% until 2050 with the strife to reach carbon neutrality as soon as possible in the second half of the century (Ministry of the Environment 2020). Recently, however, Japan’s Prime Minister Suga further increased this ambition by pledging that Japan will reach a net-zero emission society in 2050.

## 1.3 Sector coupling

In this dissertation there is a lot of emphasis on sector coupling. As the choice of technological detail and assumptions regarding the availability of certain technologies are crucial drivers, the results of energy system models largely depend on the inclusion of non-electricity sectors and sector coupling aspects. Sector coupling is generally defined as coupling the power sector with non-electricity sectors such as heating, cooling, transportation, and industry (Lund et al. 2010; Mathiesen et al. 2015; Robinius et al. 2017; Nuffel et al. 2018; Erbach 2019).

As depicted in Figure 1.3, the link between the sectors is generally established either using electricity directly as an input (e.g., power-to-heat via resistance heaters) or using electricity as input to generate hydrogen (i.e., power-to-gas via electrolysis). Hydrogen then can either be used as direct input in certain technologies (e.g., fuel cell electric vehicles, hydrogen heaters) or can be transformed into synthesis gas or methane (e.g., via methanation). The latter then can be used in existing gas-fired technologies. Linking the non-electricity sectors to the power sector either directly or indirectly then increases the overall system flexibility (Lund et al. 2017; Xiong et al. 2021). Although the term sector coupling can be found in the academic literature associated with the aforementioned linking between sectors, the term *smart energy systems* (Lund et al. 2017) and *multi-energy system* (Gabrielli et al. 2018) are used to describe similar concepts. This section presents the concept of sector coupling as well as presents the key technologies in more detail.

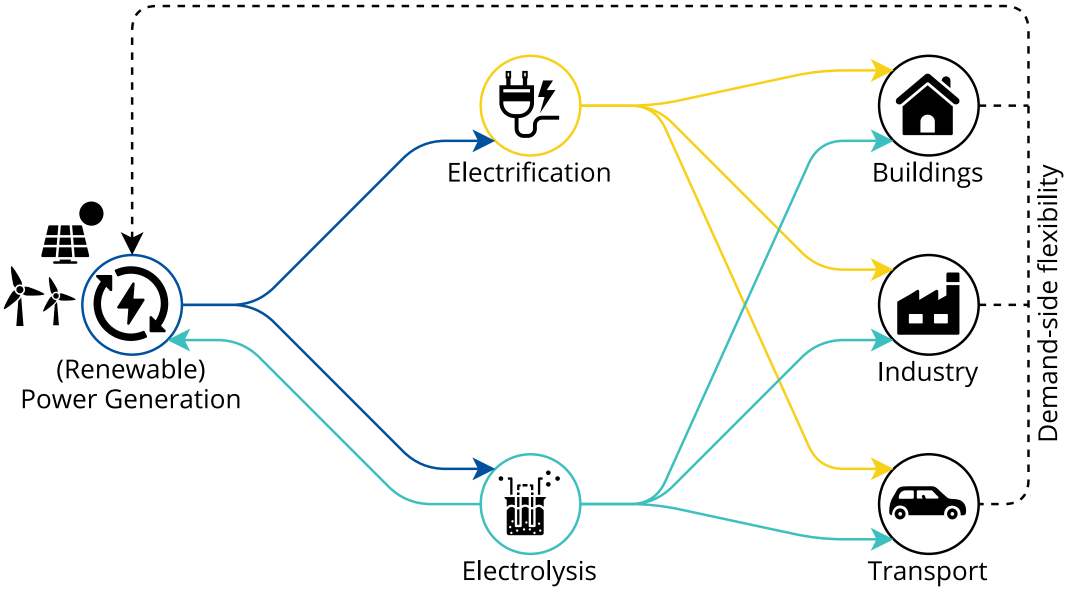

Figure 1.3: Stylistic representation of the sector coupling concept. Own depiction.

In the academic literature, sector coupling is currently mainly understood as a way to counteract the intermittent nature of variable renewable energy sources, such as solar PV or wind and to provide flexibility to the power sector (Robinius et al. 2017). Especially in 100% renewable power systems, sector coupling is deemed important for future supply stability, although only less than 60% of studies looking on 100% renewable energy sources include a multi-sectoral perspective (Hansen, Breyer, and Lund 2019). Sector coupling can provide a more flexible demand for electricity that lowers the amount of required generation capacities and storage technologies by peak-load shaving and load shifting options. Hereby, sector coupling is often seen as alternative or addition to spacial electricity balancing (Welder et al. 2018; Li, Gao, and Ruan 2019; Xiong et al. 2021). In this regard, research started to expand towards an integrated approach of the electricity and (residential) heating sector (Lund et al. 2010; Gabrielli et al. 2018; Bloess, Schill, and Zerrahn 2018). This allows for an analyzes of the positive effect on system stability of power-to-heat (direct electrification) or power-to-gas (electrolysis) in renewable-based sector coupled energy systems. Also, studies started to investigate the interaction of hydrogen-based or electrified transport with the power sector, especially in the form of vehicle-to-grid systems (Mwasilu et al. 2014; Li et al. 2020) or analyzing the value of hydrogen used with fuel-cell electric vehicles. However, just combining two sectors is not enough, as decarbonization of all sectors is required in order to reach the ambitious global climate targets of the Paris Agreement. Thus, a holistic view on sector coupling, cross-sectoral integration, and multi-energy flows is needed (Fridgen et al. 2020). The next sections present electrolysis and electrification as concepts of sector coupling and applications for the sectors buildings, industry, and transportation. Cooling is already mostly electrified and thus not considered in the next sections.

### 1.3.1 Electrification

Using electricity directly as an input fuel is often one of the most efficient ways of consuming energy. Especially when the electricity is produced using renewable energy sources, the primary energy consumption of the energy system can be substantially reduced. Overall, electricity can be used directly in every sector and in many applications directly, although current electrification technologies often have comparable high costs.

#### 1.3.1.1 Buildings sector

For providing warm water and space heating, either direct electrification or heat pumps can be used. Direct electrification generally uses electric resistance to generate heat. Hereby, the generated heat can either be dissipated directly via radiators or fans or alternatively be used to heat water which then can be used in normal residential heating circuits/networks (e.g., floor heating systems). This technology is comparatively cheap as it is already commercially available and utilized in today’s residential, commercial, and industrial buildings sector. Furthermore, direct electrification provides an almost complete conversion from electric to heating energy, thus proving to be a very efficient technology. Direct electrification can be used in central (district) heating systems and in decentral small-scale applications.

Heat pumps convert energy from outside reservoirs into energy usable for low temperature heating or the provision of warm water and cooling. In heat pumps, electricity is used to lift low exergetic (ambient) heat to a higher temperature and consequently higher exergy level by running a vapor compression cycle. Heat pumps are the only known process that recirculates environmental and waste heat back into a heat production process (Chua, Chou, and Yang 2010). The heat can be taken from sources like ambient air, water, or ground (Fischer and Madani 2017). Especially large-scale ground-source heat pumps can be used in central heating networks whereas the other types are usually only considered for decentral applications.

#### 1.3.1.2 Industrial sector

Apart from providing warm water and space heat, direct heating and heat pumps can also provide different temperatures of process heat. Especially low temperature process heat and industrial cooling can also be provided by heat-pumps for a large variety of processes (Chua, Chou, and Yang 2010). Furthermore, even medium-temperature heat generation (100 °C - 200 °C) for hot air or steam provision could be provided by specialized high temperature heat-pumps (Kosmadakis 2019).

For higher temperatures, resistance-based electrification poses currently the only option. Direct electrification can be used for generating a large variety of temperature ranges and thus can provide process heating for most industrial applications. In this regard, even steel making using recycled scrap steel can be produced using electricity in electric arc furnaces. Also, some processes already directly use electricity to a large degree. Aluminum is usually produced using a dedicated electrolysis process that uses electricity as an input fuel. This process is hoped to be used for steel making in the future as well (Wiencke et al. 2018).

Nevertheless, for most industrial technologies, direct electrification can only provide process heat and does not offer valid replacement for, currently used, fossil feedstocks. (e.g., in chemical processes).

#### 1.3.1.3 Transportation sector

In comparison to vehicles with internal combustion engine (ICE), battery electric vehicles (BEV) use electricity directly as an input fuel to generate propulsion. The electricity needed to generate the propulsion via electric motors needs to be stored in high voltage battery packs. Currently, lithium-ion or lithium-iron-phosphate battery packs are used predominantly, as they have the required energy and power density in contrast to other electric storage systems (e.g., lead batteries). The conversion of energy to propulsion via electric motors is very efficient (91–95.4 %, see Smith and Parmenter (2016)). However, current battery electric vehicles have limited ranges due to the limited energy density of the battery storages. Furthermore, they require rather long charging times and dedicated infrastructure (Michalski, Poltrum, and Bünger 2019). Increasing the range and simultaneously reducing the charging times is the current primary goals of manufacturers for BEVs. Lastly, battery electric vehicles are currently more expensive compared to internal combustion engine vehicles, due to the pricey battery storage components, although the operation and maintenance costs are lower compared to ICEs.

### 1.3.2 Water electrolysis and hydrogen applications

Another promising technology in the context of sector coupling is presented by hydrogen production from excess renewable energy via water electrolysis (also called power-to-gas). In general, hydrogen has similar properties as fossil fuels, being a burnable, gaseous energy carrier. Thus, existing conventional generation capacities could be retrofitted for utilizing hydrogen. Hydrogen is often used in sectors that are hard to decarbonize if electrification is not or only partly possible due to economic or technical reasons (Nastasi and Di Matteo 2017; Grosse et al. 2020).

#### 1.3.2.1 Buildings sector

Hydrogen can be used in two different ways for space heat and warm water production. Firstly, it can be directly burned in steam engines, (open cycle) gas turbines, or boilers to heat water that can be used either in existing district heating networks or in small-scale home applications. Boilers using hydrogen from electrolysis still can help reaching ambitious climate targets (Slorach and Stamford 2021). Further use is presented by using hydrogen within fuel cells to generate electricity and to use the waste heat as a heating source. Whereas hydrogen boilers and gas turbines facilitate mostly commercially available equipment, fuel cells are still under development. However, fuel cells, used either centrally or decentrally for combined power and heat production, can effectively provide system flexibility in the power system (Dodds et al. 2015).

#### 1.3.2.2 Industrial sector

Hydrogen can be used in nearly every process heat technology currently using fossil gas, after retrofitting existing boilers/furnaces. Additionally, for low temperature process heat provision fuel cells can be used as well. Hydrogen steam boilers are already being used by certain industrial processes and a more prominent used in future sector coupled energy systems can be assumed. Current research also investigates the role of hydrogen in steel making. In this regard, steel can be produced in an electric arc furnace with hydrogen-produced direct reduced iron (Otto et al. 2017). In other industrial subsectors, hydrogen can not only be used for heat provision, but rather as part of the industrial feedstock. Currently, hydrogen is largely used for chemical production and might be able to further replace fossil feedstocks in the chemical industry (Ausfelder and Bazzanella 2016). Also, possible hydrogen utilization in cement kilns is being investigated (Dodds et al. 2015).

#### 1.3.2.3 Transportation sector

Fuel cells can also be used in the transportation sector to provide propulsion. In general, this not only applies to cars and trucks but also potential applications of liquid hydrogen in the aviation subsector are currently being explored (Gray et al. 2021). For road-based transport, fuel cell electric vehicles have a quicker refueling process than battery electric vehicles and higher tank-to-wheel efficiencies than internal combustion engine vehicles. However, battery electric vehicles still pose to have the best overall tank-to-wheel efficiencies and fuel cell systems have similar high costs (Robinius et al. 2017). Additionally, hydrogen must be generated via electricity with further conversion losses compared to the direct usage in BEVs. Furthermore, for the large-scale introduction of fuel cell electric vehicles, substantial investments into necessary infrastructure are needed.

An alternative to directly using hydrogen is provided by power-to-fuel/power-to-liquid processes. Although named a power-to-X application, they use hydrogen (preferably produced from renewable power) together with external $CO_2$ to produce hydrocarbon liquids (e.g., synthetic diesel or kerosene) (Drünert et al. 2020; Schorn et al. 2021). However, these processes require successful and large-scale applications of carbon capture, transport, and storage (CCTS). As the technological availability of large-scale deployment of CCTS is still uncertain (Oei and Mendelevitch 2016; Minx et al. 2018), the overall success of power-to-liquid applications is still uncertain. Furthermore, power-to-liquid fuels' versatility is counterbalanced by their fragile climate effectiveness, high costs and uncertain availability. Furthermore, neglecting demand-side transformations threatens to lock in a fossil-fuel dependency if e-fuels fall short of expectations (Ueckerdt et al. 2021). Also, the most critical aspect for the deployment of power-to-Liquid applications is the large-scale availability of direct-air-capture DAC technology. Currently only small- to medium-scale prototype plants are in operation with a commercialization of the technology still uncertain (Ueckerdt et al. 2021).

## 1.4 Energy systems models

In general, energy system models are mathematical optimization models which aim to represent parts of or entire energy systems. In this regard, the energy system is defined as the *"[...] system [that] comprises all components related to the production, conversion, delivery, and use of energy"* (Allwood et al. 2014). The spectrum of existing models varies substantially, with each formulation focusing on different aspects of energy systems. The system approach was originally proposed by the biologist Bertalanffy (1950, 1957). While traditional analyses mostly relied on separating the object of what is being studied, the system approach focuses on the interactions between the matter being investigated and all other parts of the system (Nakata, Silva, and Rodionov 2011). In this regard, energy system models are able to convey the big picture of what is happening in different (sometimes interlinked) sectors of an energy system.

Historically, popularity of energy system models increased over the last decades, since they conducted and computed compelling energy system analyses after the first oil crisis in 1973. From there on, accelerated by the availability of computational resources, the number of energy system models increased rapidly to analyze the efficient use of final energies (Connolly et al. 2010; Herbst et al. 2012; DeCarolis et al. 2017). In recent years, the focus shifted towards a more long-term perspectives to identify challenges and developments in the broader picture of climate change (Bhattacharyya and Timilsina 2010).

### 1.4.1 Classification of energy systems models

The spectrum of energy system models is widespread with various diverse modeling concepts utilized for different purposes. In this regard, several classifications have been developed to simplify the comparison of energy system models (Grubb et al. 1993; Wene 1996; Nakata 2004; Jebaraj and Iniyan 2006; Connolly et al. 2010; Herbst et al. 2012; Pfenninger, Hawkes, and Keirstead 2014; Hall and Buckley 2016; Prina, Manzolini, et al. 2020). Typically, the most general classification of energy system models is presented by the division into top-down and bottom-up models, distinguished by their level of technological detail and representation of market features (Wene 1996; Hourcade et al. 2006; Böhringer and Rutherford 2008; Herbst et al. 2012).

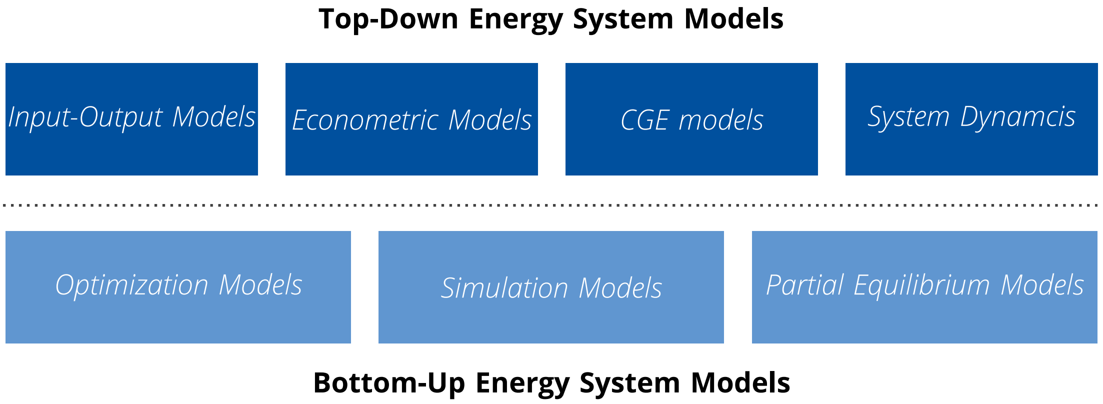

Figure 1.4: Classification of energy system models. Own depiction based on Herbst et al. 2012.

Top-down models sacrifice detailed technical information for a better macroeconomic representation. They try to depict entire national or regional economies while looking at aggregated effects of climate, energy, or societal change. Therefore, the key-drivers for top-down models are often economic growth, inter-industrial structural change, demographic development, and price trends. Figure 1.4 presents the different types of energy system models within their respective classifications.

Firstly, *Input-Output* models are used for a structural description of the energy system by following the total flows of money, commodities, goods, or services between different sectors of the economy. Based on historical data, *Input-Output* models are able to evaluate short-term effects of policies, as well as estimate monetary effects of economic shocks. They are able to provide a detailed static snapshot of an economy but unable to present the transitioning from one status of the economy to another. As an example, the United Nations use an input-output analysis for coherent estimates of GDP (United Nations 1999).

Secondly, *Econometric* models combine economic theory with statistical and mathematical methods to estimate statistical relations between economic variables over time. Usually, *Econometric* models correlate energy demand with other macro-economic variables, such as GDP or population development, to forecast the future development of energy consumption (Suganthi and Samuel 2012). Although these types of models rely on substantial amounts of data in order to generation stochastically significant results, they can be used to analyze the long-term effects of policies on the energy system. The energy–environment–economy model for Europe (E3ME) is a sectoral, econometric model of the EU which has been modeled by a team of partner institutes across Europe with Cambridge Econometrics acting as coordinator (Barker 1998).[3]

Thirdly, *Computable general equilibrium (CGE) models* are based on the microeconomic theory of a general equilibrium.[4] CGE models can be seen as a generalization of *Input-Output* models. In general, *CGE* models can be used for long-term simulations of future energy systems. They are able to analyze the full consequences of policy effects on the investigated system and usually represent the circular flow of goods and services in an economy (Jacoby et al. 2006). Nevertheless, *CGE* models often neglect the importance of market failures and do not take technological details into account (Hourcade et al. 2006). Prominent examples of *CGE* models are the MIT Emissions Prediction and Policy Analysis (MIT-EPPA) model by Paltsev et al. (2005) used to simulate the world economy and the General Equilibrium Model for Economy-Energy-Environment (GEM-E3) by Capros et al. (2013).

Lastly, the modeling concept of *System Dynamics* was introduced in the 1950s at the Massachusetts Institute of Technology (MIT) by Forrester (1958). In general, *System Dynamics* models are based on system thinking to understand and analyze the behavior and activities of different actors in complex systems over time. Hereby, *System Dynamics* models utilize various control factors such as feedback loops and time delays to observe how the system reacts and behaves to trends (Aslani, Helo, and Naaranoja 2014). Furthermore, the concept of *System Dynamics* is sometimes applied in bottom-up energy system models, e.g.,

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[3] See https://www.camecon.com/how/e3me-model/; last accessed: 03.03.2021.

[4] Developed by Léon Walras in the 1870s.

POLES (Prospective Outlook on Long-term Energy Systems) (Criqui 1996; Russ and Criqui 2007).

In contrast to top-down models, bottom-up models excel at depicting techno-economic aspects of energy systems allowing a detailed representation of technical aspects. This representation enables the impact analysis of single technologies on the whole energy system or consequences of sectoral policy decisions. In contrast, they usually lack the ability to depict very long-term time horizons with short re-investment cycles, as well as some important macro-economic factors (Wene 1996; Hourcade et al. 2006; Herbst et al. 2012).

In general, bottom-up *Optimization Models* are used to determine an optimal choice of technologies at minimized costs under certain constraints. They endogenously calculate required technology investments and dispatch in order to generate a stable energy system. *Optimization Models* are able to analyze an energy system with differing regional, temporal, and sector aggregation and allow an analysis on a detailed technology level. In contrast, *Optimization models* often so not account for the -sometimes severe- market imperfections and societal obstacles in energy sectors. Recent research also incorporates market power exertion to social welfare maximization models by adding appropriate terms accounting for market power exertion (Egging-Bratseth, Baltensperger, and Tomasgard 2020). One of today's most known models is the MARKAL model, developed by the International Energy Agency (Fishbone and Abilock 1981). While MARKAL belongs to the group of optimization models, current modules try to bridge the gap between the techno-economic and macroeconomic models (Seebregts, Goldstein, and Smekens 2002), one of them being TIMES (The Integrated MARKAL-EFOM System). TIMES combines technical engineering with an economic approach, thus merging the characteristics of both (Loulou and Labriet 2008).

*Simulation Models* represent a different kind of bottom-up models that do not use mathematical optimization techniques but rather try to replicate the consecutive rules that describe the associations and interrelationships among various system elements (Herbst et al. 2012). Instead of generating optimal cost-minimizing or profit-maximizing pattern, *Simulation Models*, observe decisions and technological choices through multiple different scenarios within a complex system. In this regard, the World Energy Model (WEM) being one *Simulation Model* which had probably the most impact in recent years. It is used by the International Energy Agency (IEA) to determine the scenarios for the World Energy Outlook and is designed to replicate how energy markets function (International Energy Agency 2021). Furthermore, a simple form of simulation models consist of accounting framework models (Mundaca and Neij 2009), for example, the Long-Range Energy Alternatives Planning Model (LEAP), which was developed by the Stockholm Environment Institute (Heaps 2008).

LEAP is designed around the modeling and simulation of different scenarios which then can be compared to each other to provide insights about possible future energy system developments and support for policymakers.

*Partial Equilibrium Models* are another type of bottom-up models. In general, this type follows a similar mathematical approach as *CGE* models. But by neglecting certain interrelations and effects on the broader economy, *Partial Equilibrium Models* can include many more technological details than conventional *CGE* models. The Price-Induced Market Equilibrium System (PRIMES) that is used by the European Commission for long-term analyses of the European energy system is one of the most prominent *Partial Equilibrium Models*. PRIMES is used to analyze, for example, the impacts of carbon emission trading and of renewable and energy efficiency policies on energy markets (E3MLab 2018). Another example is the energy system and resource market model MultiMod (Huppmann and Egging 2014). MultiMod is a large-scale representation of the supply and demand of fossil fuels and renewable energy sources. The model incorporates important market features, such as endogenous fuel substitution and market power, into the field of energy systems modeling.

### 1.4.2 Review of bottom-up energy system models

As this dissertation focuses on the role of specific technologies in the low-carbon energy transformation, top-down models were not considered because of their lack of technological and sectoral detail. Instead, I have chosen to develop a bottom-up multi-sectoral energy system model.

In general, bottom-up energy system models enable detailed analyses of the future role and impact of technologies in one or multiple sectors with a sophisticated regional and temporal level of detail. Therefore, they pose an excellent tool for assessing low-carbon transformation pathways for either regional or global energy systems. Furthermore, bottom-up simulation and optimization models are easy to scale, expand, and enhance, thus allowing a broader audience to conduct energy system analyses. These characteristics of bottom-up models lead to an increased development of models and frameworks. Especially with the current movement of open data and open source, adjustable open source energy system frameworks have become more prominent and are being used in a multitude of different applications.

Table 1.1: Recent bottom-up energy system model applications, their modeling approach, and their sectoral coverage.

| **Name** | **Method** | **Sectors** | **Reference** |
|---|---|---|---|
| Balmorel | Partial Equilibrium | Electricity, District Heating | Wiese et al. (2018) |
| Calliope (Framework) | Optimization | flexible | Pfenninger and Pickering (2018) |
| Calliope | Optimization | Electricity | Pfenninger and Keirstead (2015) |
| DESSTinEE | Simulation | Electricity | Boßmann and Staffell (2015) |
| EnergyPLAN | Simulation | Electricity, Cooling, (Residential and industrial) Heating, Transport | Lund (2014) |
| Genesys | Simulation | Electricity | Bussar et al. (2016) |
| LUT | Optimization | Electricity | Breyer et al. (2017) |
| LUT | Optimization | Electricity, Heating, Transport, Desalination | Bogdanov et al. 2021 |
| oemof (Framework) | Optimization | flexible | Hilpert et al. (2018) |
| oemof-moea | Optimization | Electricity | Prina, Casalicchio, et al. (2020) |
| OSeEM-DE (baed on oemof) | Optimization | Electricity, Heating | Maruf (2021) |
| OSeMOSYS (Framework) | Optimization | flexible | Howells et al. (2011) |
| OSeMOSYS | Optimization | Residential sector | Leibowicz et al. (2018) |
| OSeMOSYS | Optimization | Electricity | Rady et al. (2018) |
| OSeMBE | Optimization | Electricity | Henke, Howells, and Shivakumar (2018) |
| OSeMOSYS SAMBA | Optimization | Electricity | Moura, Legey, and Howells (2018) |

Recent bottom-up energy system model applications, their modeling approach, and their sectoral coverage (continued).

| **Name** | **Method** | **Sectors** | **Reference** |
|---|---|---|---|
| GENeSYS-MOD (based on OSeMOSYS) | Optimization | Electricity, (Residential and industrial) Heating, Transport | Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) (Chapter 2 of this dissertation) |
| PRIMES | Partial Equilibrium | All | E3MLab (2018) |
| PyPSA (Framework) | Optimization | flexible with focus in Electricity | Brown, Hörsch, and Schlachtberger (2018) |
| PyPSA | Optimization | Electricity | Schlachtberger et al. (2017) |
| REMix | Optimization | Electricity, Heat | Gils et al. (2017) |
| Temoa (Framework) | Optimization | flexible | Hunter, Sreepathi, and DeCarolis (2013) |
| Temoa | Optimization | Electricity, Transport | DeCarolis et al. (2016) |
| TIMES | Optimization | All | Loulou and Labriet (2008) |
| urbs (Framework) | Optimization | Flexible | Dorfner (2016) |
| urbs | Optimization | Electricity | Stüber and Odersky (2020) |

Currently, several closed and open source frameworks and energy system models are available, as being presented in Table 1.1. Most of these bottom-up models belong to the optimization model sub-type and encompass at least the electricity sector. With regard to the sectoral coverage, different types can be observed:

1. Models focusing only on specific sectors
2. Frameworks with a flexible formulation
3. Commercial models considering all sectors of an energy system

The primary difference between models and frameworks considered in this review is the flexibility and applicability of the models. Frameworks are considered to have a flexible structure in regional, temporal, or sectoral level of detail, are openly available and thus can be easily adjusted and utilized by a large majority of users. In contrast, models are in general fixed in most of the scopes and are enhanced only within complex model enhancements instead of a general flexible structure.

Within the first type, most models focus either directly on the power sector (i.e, *DESSTinEE*, *Genesys*, and *LUT* (Breyer et al. 2017)) or include the power sector and (district) heating (i.e, *Balmorel* and *REMix*). The *LUT* model, however, has recently been updated by (Ram et al. 2019) with a complete representation of most sectors of an energy system (including the desalination sector for drinking water provision).

Following the simulation approach, the *DESSTinEE* (Demand for Energy Services, Supply and Transmission in EuropE) is a Microsoft Excel and VBA simulation energy system model to analyze the European Energy System in 2050. It solely focuses on the electricity sector and can simulate the least-cost dispatch and transmission of electricity (Boßmann and Staffell 2015; Oberle and Elsland 2019). Although final energy demands for other sectors are considered, these are not modeled explicitly and are just used to generate the hourly electricity demand profiles for 2050. Due to the format of the input-sheets in Microsoft Excel, expanding the technology options of *DESSTinEE* can hardly be done without substantial changes in model and code. However, adjusting the existing input parameters and running the model is very accessible due to the aforementioned structure.

Also pursuing a simulation approach, the model *Genesys*[5] is able to find the optimal power system configuration for a given target year, taking into consideration the then-existing power plants. It can furthermore calculate a transformation pathways to decarbonize the system following boundary conditions like the EU targets. *Genesys* itself is written in C++ and uses a genetic algorithm that composes new systems randomly and evaluates the systems by simulation. The model covers the geographical regions of Europe, Middle East, and North Africa and calculates an hourly power system dispatch (Bussar et al. 2016). However, non-electricity sectors as well as an explicit modeling of sector coupling aspects are completely missing in the *Genesys* model.

The energy system model *Balmorel* was originally created for an analysis of electricity and district heating markets in the Baltic Sea region. It is formulated as an partial equilibrium

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[5] In this dissertation, also the energy system model *GENeSYS-MOD* (Global Energy System Model) will be presented and used. Although the naming is similar, *Genesys* as presented by Bussar et al. (2016) and *GENeSYS-MOD* as presented in Chapter 2 of this dissertation have completely different origins, model paradigms, and scopes.

model and maximizes social surplus subject to techno-economic constraints (Juul and Meibom 2011). The formulation of *Balmorel* is flexible regarding the spatial and temporal resolution (Wiese et al. 2018). Nevertheless, sectoral coverage is rather static and can only be increased by writing full-fledged model add-ons. In this regard, Juul and Meibom (2011) have expanded the model with an additional transport module and Karlsson and Meibom (2008) have included hydrogen production, storage, and consumption in the power sector of *Balmorel*.

Another energy system model with high temporal and spatial resolution is presented by *Renewable Energy Mix (REMix)* energy system model (Gils et al. 2017). The model itself is written in the General Algebraic Modeling System (GAMS) and is focused on the integration of variable renewable energy sources into the power sector. Furthermore, endogenous capacity expansion and dispatch of residential heating systems is considered in the model. Studies using REMix also investigated the impact of electric vehicles on the power system (Luca de Tena and Pregger 2018) and the economic potential of demand response (Gils 2016).

Focusing on optimizing the global energy system with a sophisticated regional and temporal coverage, the *LUT* model was originally tailored to focus on the power sector (Breyer et al. 2017; Bogdanov et al. 2019). With a special focus on the role of solar PV and electricity storage systems for the energy transition, several global and detailed regional case studies have been published by the core developers of the model (Bogdanov and Breyer 2016; Gulagi et al. 2017; Aghahosseini, Bogdanov, and Breyer 2017; Bogdanov et al. 2019). Furthermore, the model has been enhanced by representing multiple non-electricity sectors and sector coupling options in the recent study by Ram et al. (2019) and Bogdanov et al. (2021). However, the code is not publicly available and, thus, the possibility to adjust the model and data of the *LUT* model stay unclear.

*EnergyPLAN* is also an openly available model following the simulation approach. It focuses on the design and evaluation of renewable energy systems with high penetration of fluctuating renewable energy sources on an hourly basis (Lund 2014). The model simulates the heating, cooling, electricity, transport, and industry sectors. However, in the non-electricity sectors, specific fuel demands are given exogenously, such that the model has limited options to invest into sector coupling technologies endogenously. Adding new technology options is not easily possible. Furthermore, only one geographical region without the consideration of power transmission or fuel transport can be simulated at a time.

Within the second type, a plethora of frameworks with a flexible formulation for modeling energy systems is available. Almost all of them allow for including non-electricity sectors and sector coupling aspects due to their often flexible mathematical formulation. However, most applications based on these frameworks only consider the power sectors.

*Calliope* is an optimization-type energy system modeling framework with a focus on high spatial and temporal resolution with a scale-agnostic mathematical formulation permitting analyses ranging from single urban districts to countries and continents (Pfenninger and Pickering 2018). It is built in Python and considers a generalized formulation of energy carriers in order to allow the user to easily increase the sectoral coverage. Nevertheless, most recent publications utilizing *Calliope* consider the power sector only, despite the flexible framework's formulation (Pfenninger and Keirstead 2015; Hilbers, Brayshaw, and Gandy 2019; Tröndle et al. 2020).

The *Open Energy Modelling Framework (oemof)* is an open-source toolbox for the representation, analysis, and modeling of the power and non-electricity sectors. The model strongly facilitates open science with a highly transparent collaborative cross-institutional software development (Hilpert et al. 2018). Its structure is adjustable and allows for modeling an energy system with different levels of regional and temporal (up to hourly) aggregation. However, although the model itself poses a flexible basis for energy systems analysis, recent studies consider only the power system, neglecting sector coupling aspects in their analyses (Prina, Casalicchio, et al. 2020; Maruf 2021).

With a similar approach regarding its flexible formulation of regional, temporal, and sectoral coverage, the *Open Source Energy Modeling System (OSeMOSYS)*, was originally created to allow a broader community of modelers to pursue sophisticated energy systems analyses (Howells et al. 2011). *OSeMOSYS* is a linear energy system model optimizing the net present value of an energy system. In general, the model framework follows the structure of long-established closed sources energy system models such as *TIMES* (Gardumi et al. 2018). Furthermore, it features an easy to understand mathematical formulation that can be easily enhanced by the users of the framework. Also, *OSeMOSYS* is available in a range of programming languages (i.e., GMPL, GAMS, Python), such that a broad audience is able to work with the framework. Due to its adaptability and openness, several publications utilizing *OSeMOSYS* with different regional and sectoral focuses have been published by various researchers (Welsch et al. 2012; Lyseng et al. 2016; Taliotis et al. 2016; Taliotis et al. 2017; Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Leibowicz et al. 2018). However, most of these studies consider only one distinct sector. An expanded version of *OSeMOSYS*, the *Global Energy System Model (GEnESYS-MOD)* is used in this dissertation and the model description, as well as a global case study, can be found in Chapter 2.

The *Python for Power System Analysis (PyPSA)* is a sophisticated software toolbox for modeling and optimizing modern electrical power systems over multiple periods. It features detailed power system aspects, such as nonlinear direct current (DC) flows or unit commitment constraints. *PyPSA* is openly available with its full mathematical formulation and implementation in Python. However, although the framework itself allows for links to other sectors, recent studies often target the power sector in high detail while neglecting the future effects of sector coupling and electrification of non-electricity sectors (Schlachtberger et al. 2017; Hörsch et al. 2018).

The *Tools for Energy Model Optimization and Analysis (Temoa)* is a framework for bottom-up energy system optimization based on a flexible structure similar to the one presented by *OSeMOSYS* or *oemof*. However, the model is built around the idea of iterating over large amounts of model runs to understand how key uncertainties can drive the model results (Hunter, Sreepathi, and DeCarolis 2013). In this regard, *Temoa* was also refined using stochastic programming allowing for stochastic optimization of a simple model with 81 scenarios across 3 time-stages. *Temoa* has also being used in a Modeling to Generate Alternatives (MGA) approach targeting the electricity and light-duty transport sector (DeCarolis et al. 2016).

*Urbs* is a linear programming optimization framework for multi-commodity energy systems with a focus on optimal storage sizing and use. It allows for a flexible regional and sectoral level of details within an hourly resolution. *Urbs* is written in Python and openly available. In a recent study by Stüber and Odersky (2020), it is used to implement stochastic dual dynamic programming and apply it to the case of Germany, only optimizing the power sector.

Lastly, there are two well-known large-scale but mostly commercially available models. *PRIMES* being closed source and unavailable for most researchers and the *TIMES* model family which is only commercially available. However, in contrast to *PRIMES*, the model code of *TIMES* is openly available, with low charges for research institutes and Universities. Both models are able to compute energy transformation pathways for all energy system sectors.

Most commonly known for the generation of the EU Reference scenarios (European Commission 2016b), the *Price-Induced Market Equilibrium System (PRIMES)* is based on a sophisticated mathematical formulation and database. The partial equilibrium model covers the European energy system in great sectoral detail (Capros et al. 2012; E3MLab 2018) and is used to quantify the energy and climate goals in the EU. However, the model is closed-source with only limited information available regarding its data sets, mathematical formulation, and key model assumptions. Thus, the model itself as well as the heavy reliance of the European Commission on the *PRIMES* modeling suite can be seen as critical regarding transparency and robustness of results (Earl, Mathieu, and Calvo Ambel 2018; Wildauer, Leitch, and Kapeller 2020).

*The Integrated MARKAL-EFOM System (TIMES)* is a commercially available energy system model originally presented by Loulou and Labriet (2008). The model was developed under the IEA *Programme of Energy Technology Systems Analysis (ETSAP)*[6] and is currently one of the most used model generators for energy systems analyses. *TIMES* is a technology-rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy system. In general, *TIMES* combines two different, but complementary, systematic approaches to modeling energy: a technical engineering approach and an economic approach. It uses aggregated annual time-slices instead of an hourly resolution but is flexible in its geographic coverage and usually encompasses all sectors of the energy system. *TIMES* has been used in several applications focusing on various different global regions (McDowall et al. 2018; Kato and Kurosawa 2019; Li, Chen, and Zhang 2020; Di Leo et al. 2020).

Overall, it can be seen that although commercially available models like *TIMES* or *PRIMES* already include non-electricity sectors and sector coupling aspects, those are neglected in many non-commercial applications. Additionally framework-applications that do explicitly offer the ability to include non-electricity sectors are often only used for single-sector power systems analyses. However, as presented in Chapters 4 to 6 of this dissertation, sector coupling will play a crucial role in future decarbonized energy systems and, thus, should be considered within current energy systems analyses.

### 1.4.3 Open science and energy systems modeling

In recent years the concept of *open science* has gained increased interest in the scientific community, although in the past, most energy system models have been developed commercially, were closed-sourced, and did not publish their underlying data sets and assumptions sufficiently. Open Science is defined as transparent and accessible knowledge that is shared and developed through collaborative networks (Vicente-Saez and Martinez-Fuentes 2018). With open science becoming more prominent in the scientific community, even the European Commission now has a clear statement published on the topic of open science, making it a necessity for future funding (European Commission 2021). In this regard, the term open science also encompasses the ideas of *open access*, *open source*, and *open data*.

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[6] Compare https://iea-etsap.org/; last accessed 31.03.2021

*Open access* refers to the idea of making academic and scientific publications freely available, such that it can be accesses without any barriers, by scholars and individuals.

*Open source* is used generally in a software development context. It refers to publishing the complete source code of a program and thus allowing others the option to modify and change parts of the program. Within the community of energy system modelers this concept also applies to the mathematical equations and model setup of energy system models.

*Open data* is referring to make the underlying data of a program or model freely available without applying strict licensing clauses. The goal of open data is to increase the transparency and reproducible of mathematical models and programs.

The trend of becoming more open can also be observed within the field of energy system modeling. On the one hand side, a plethora of modeling frameworks have been developed inherently implementing the ideas of open source and open data. Examples for these frameworks include i.a., oemof[7], OSeMOSYS[8], or PyPSA[9]. On the other hand side, with open science being recognized and legitimized by the scientific community as good standard for research (Krishna 2020), also traditionally commercial closed source models are becoming openly available. The most prominent example is hereby TIMES, which has becoming open source in December 2019.[10]

### 1.4.4 Goal and vision of GENeSYS-MOD

The primary goal of GENeSYS-MOD is to have an openly available integrated calculation of technology investment and operation in all sectors of the energy system. In this regard, Table 1.2 compares GENeSYS-MOD to two other energy system models to highlight the differences in chosen model paradigms and goals.

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[7] See https://github.com/oemof; last accesses 02.04.2021.

[8] See https://github.com/OSeMOSYS; last accesses 02.04.2021.

[9] See https://github.com/PyPSA; last accesses 02.04.2021.

[10] See https://github.com/etsap-TIMES; last accesses 02.04.2021.

Table 1.2: Comparison of modeling approaches

| **Characteristic** | **Sub-characteristic** | **GENeSYS-MOD** | **LUT** | **EnergyPLAN** |
|---|---|---|---|---|
| Modeling Approach | | optimization | optimization | simulation |
| Temporal configuration | Intra-annual resolution | integrated[11] | sequential[12] | single year |
| | Inter-annual resolution | time-slices/reduced hourly/stochastic | full hourly | full hourly |
| Spatial configuration | Regional coverage | Multi-regional | Multi-regional | Single region |
| Sectors considered | Electricity | A | A | C |
| | Residential heating | A | A | D |
| | Prosumers and individual heating | - | B | - |
| | Industry | A[13,14,15] | A[16] | D |
| | Transport | A | C[17] | D |
| | Desalination | - | A | D |

With the following ranks as depicted in the sectoral configuration:

**A** - Integrated endogenous optimization of technology investments and operation
**B** - Sub-model endogenous optimization of technology investments and operation
**C** - Integrated endogenous optimization of technology dispatch/operation
**D** - Exogenously defined demand and supply shares

As shown in this table, various models are able to generate different insights due to the sectoral, temporal, and spatial configurations they have chosen. For example, GENeSYS-MOD misses a full-hourly resolution compared to EnergyPLAN or the LUT model but instead aims for the aforementioned integrated optimization of investments and operation across the whole modeling period. On the other hand, EnergyPLAN, for example, is used to generate multiple scenarios or sensitivities without substantial calculation times, which leads to the choice of the corresponding spatial and sectoral configurations chosen.

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[17] Integrated optimization across the whole model horizon from base-year until target year.

[17] Sequential optimization across the whole model horizon from base-year until target year. Hereby, the results of the previous year are used in the calculation of the next year.

[17] Low, and high industrial heat (v1.0)

[17] Low, medium, high industrial heat (v2.0-v3.0)

[17] Aluminum, Copper, Ammonia, Chlorine, Iron & Steel, Lime, Glass, and Cement with part of the intermediate products (stochastic GENeSYS-MOD (Chapter 6))

[17] Low, medium, high industrial heat

Overall, model results also strongly depend on the choice of mathematical formulation, modeling approach, and inclusion of elements (e.g., salvage values, depreciation rates, discounting/discount rates). However, I want to stress that no model is better or superior compared to others, as all models are subject to their assumptions. Hence, no model should be used to generate forecasts but insights (Box 1976; Huntington, Weyant, and Sweeney 1982). Currently, computational resources are still limited. Therefore, the model/tool should be chosen considering the purpose and original research question, as no model fits all possible research questions. In this regard, also a modeling suite consisting of various models should be considered depending on the research questions.

Overall, GENeSYS-MOD excels at calculating final sectoral demands for fuels or electricity, which can be used by more specialized models within a broader modeling suite, for example. Therefore, I envision GENeSYS-MOD as central and integral part of a larger modeling suite, as presented in Figure 1.5

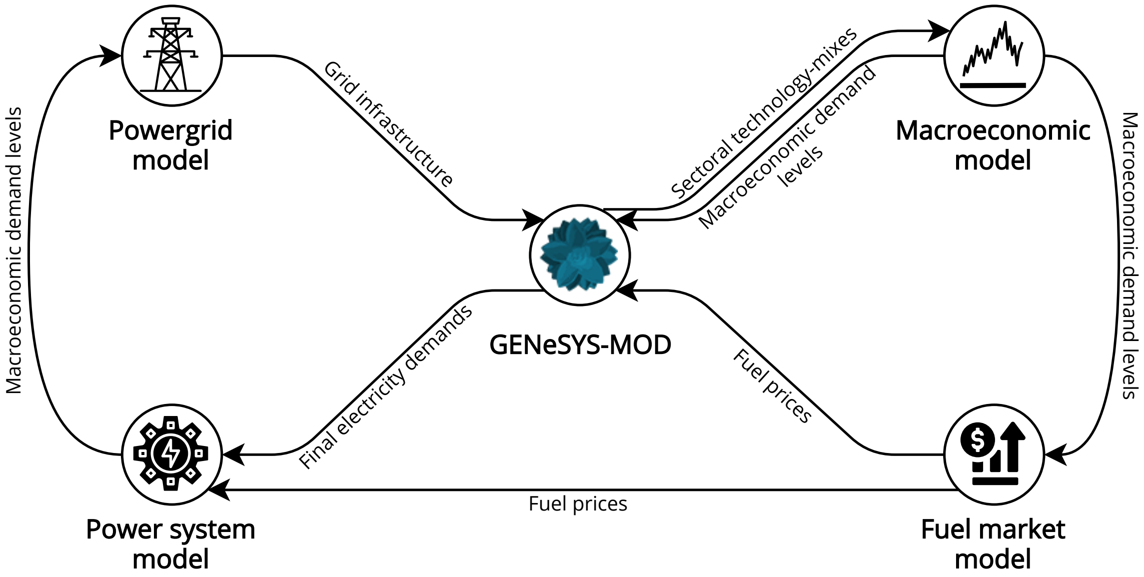

Figure 1.5: GENeSYS-MOD as integral part of a larger modeling suite. Own depiction.

## 1.5 Outline of the dissertation

In this doctoral thesis, I develop the energy system model GENeSYS-MOD (Global Energy System Model) which is applied in several regional case studies to analyze specific research question in light of a low carbon energy system transformation. The thesis is structured in two parts and consist of 5 research articles that have been published or are under review in peer-reviewed international journals. Other publications with GENeSYS-MOD that are not part of this dissertation but have been co-authored by me can be found in Appendix A. The structure of the dissertation is depicted in Figure 1.6.

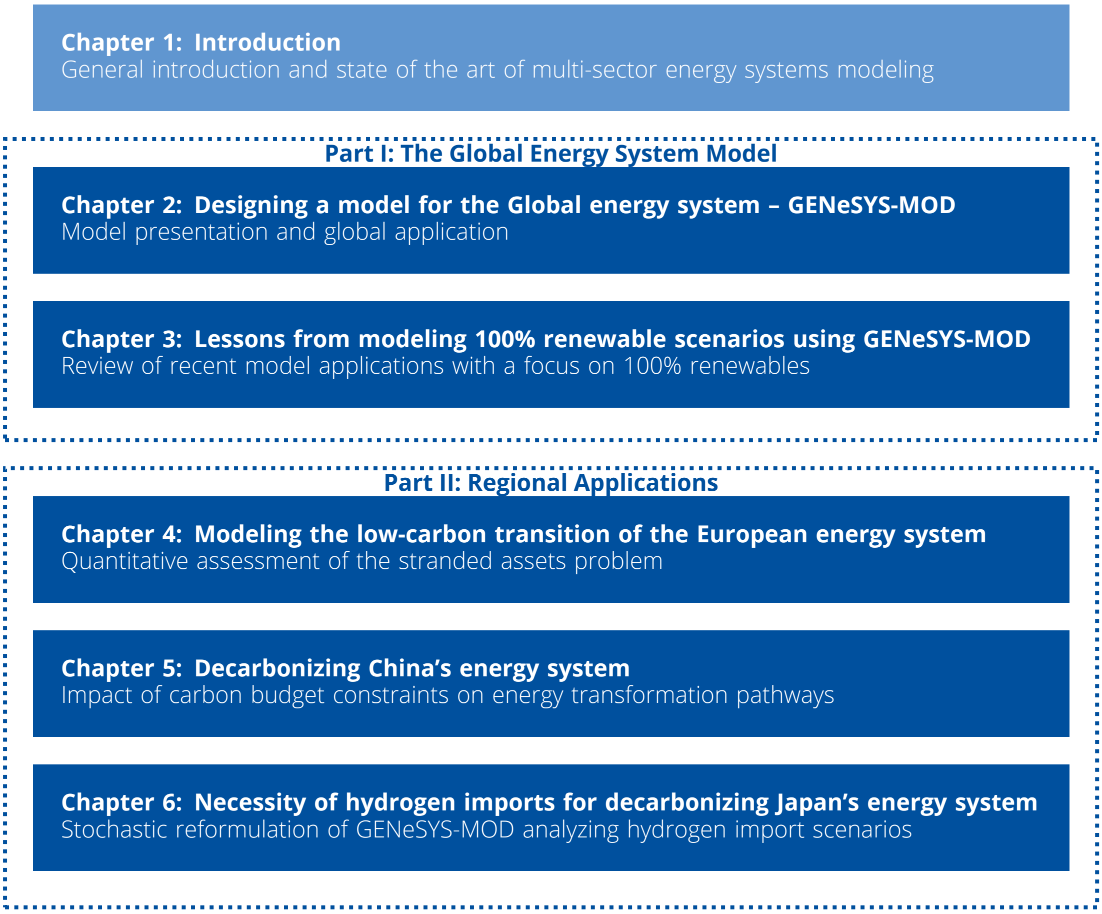

Figure 1.6: Outline of the dissertation. The chapter origins and own contributions are presented in Section 1.5.6.

Part I of this dissertation presents GENeSYS-MOD in Chapter 2 as well as giving an overview of recent 100% renewable analyses using GENeSYS-MOD in Chapter 3. In Part II several regional applications are presented. First, the stranded assets problem in Europe is being investigated in Chapter 4, followed by an in-depth analyses of the impact of carbon budgets on Chinese energy system transformations pathways in Chapter 5. Lastly, Chapter 6 focuses on the necessity of hydrogen imports for Japan's ambitious climate targets to reach a decarbonized society by 2050.

### 1.5.1 Chapter 2: Designing a model for the Global energy system –GENeSYS-MOD

In this chapter the Global Energy System Model (GENeSYS-MOD) based on the open-source energy modeling system (OSeMOSYS) is presented with its key characteristics. GENeSYS-MOD uses a system of linear equations to represent the transformation of the energy system. The model optimizes the net present value of an future energy system, given externally defined constraints, mainly in terms of $CO_2$-emissions, techno-economic assumptions, and policy targets. The general algebraic modeling system (GAMS) version of OSeMOSYS is updated to the newest version and, in addition, extended and enhanced to include i.a., a modal split for transport, an improved trading system, and changes to the storage representation.

Due to the flexible structure of GENeSYS-MOD, the model can be applied from small-scale local applications to large-scale global applications. In this chapter, an application of GENeSYS-MOD for the global energy system is presented. The global energy system is represented using 10 aggregated regions and the time-frame 2015 until 2050 is modeled and a global carbon budget of 650 $GtCO_2$[18] that can be emitted until 2050 is assumed. As a key contribution to the existing literature, this application of GENeSYS-MOD primarily focuses on the interdependencies between traditionally segregated sectors: electricity, transportation, and heating; which are all included in the model. Thus, a holistic and integrated analysis of the energy system transformation is being represented.

Model calculations suggest that in order to achieve the 1.5–2 °C target, a combination of different renewable energy sources is required and provides the lowest-cost solution. In general, the model results suggest a reorientation of the energy system, driven mainly by climate constraints and decreasing costs of renewable energy sources. As the carbon constraint becomes more binding, fewer fossil fuels are used to supply energy and a gradual shift towards renewable sources is observed, accompanied by increased sector coupling in the form of electrification and the large-scale introduction of hydrogen into the energy system. Overall, the energy mix in 2050 is based on wind and solar power, biomass, and hydropower as the main energy sources, with solar photovoltaic being the dominant source. To a smaller degree, geothermal and tidal power plants provide energy as well. Depending on the region, some fossil fuels are phased out as early as 2035 with most fossil fuels being replaced by 2045. Overall, the energy system is based 100% renewable energy sources in

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[18] 33% - 50% likelihood of limit global warming to 1.5–2 °C (IPCC 2013)

2050. The global average costs of electricity generation in 2050 are about 4 €cents/kWh (excluding infrastructure and transportation costs).

### 1.5.2 Chapter 3: Lessons from modeling 100% renewable scenarios using GENeSYS-MOD

This chapter presents specific characteristics and challenges for modeling sector coupled energy systems, based on 100% renewables. When Jacobson et al. (2015) presented their study of an energy system solely based on wind, water, and solar for the United States, their assumptions, results, and conclusion were highly criticized by Clack et al. (2017). This started an ongoing discussions about the general feasibility of 100% renewable energy systems, which is still ongoing (compare Loftus et al. (2015), Heard et al. (2017), and Brown et al. (2018)). However, in recent years, the discussion of 100% renewable scenarios shifted from general feasibility issues to specific assumptions (Creutzig et al. 2017; Egli, Steffen, and Schmidt 2019; Mohn 2020).

The findings presented in this Chapter are based on various applications and modifications of GENeSYS-MOD examining different regional characteristics for high renewable configurations in the world, China, India, South-Africa, Mexico, Europe, Germany, and Colombia. The paper elaborates on experiences of the last years of choosing the best, yet still computable, configuration of GENeSYS-MOD with respect to spatial and temporal resolution as well as sufficiently detailed description of the sector coupled energy system transition effects.

Overall, this chapter highlights that models largely depend on taken assumptions, including in particular the choice of data, sometimes having to be estimated far into the future. Thus, model assumptions, data, and their limitations are clearly stated and discussed can there be a fruitful discourse on the results that have been gained. This chapter contributes on the debate on specific assumptions in energy system models started by Creutzig et al. (2017), Egli, Steffen, and Schmidt (2019), and Mohn (2020). Furthermore, it showcases how to improve future modeling exercises by profiting from the experience gained over the last few years.

### 1.5.3 Chapter 4: Modeling the low-carbon transition of the European energy system

In this chapter, multiple pathways for the European energy system until 2050 are computed, focusing on one of the major challenges of the low-carbon transition: the issue of unused capacities and stranded assets. In this regard, stranded assets are defined as assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities (Caldecott 2018). Globally, the loss due to stranded assets in the energy sector may amount to \$2-\$4 trillion until 2040 (Carbon Tracker Initiative 2015; Mercure et al. 2018).

Three different scenarios are analyzed, utilizing the GENeSYS-MOD for calculations. A major feature is the introduction of limited foresight and imperfect planning to the multi-sectoral approach of the model. A baseline scenario is compared to a scenario with reduced foresight and one scenario with reduced foresight and additional political constraints. In the last one, existing fossil power generation lifetimes are extended exogneously as a policy measure.

Results show that a swift transition towards renewable energy sources is needed in order to ensure the goal of staying below 2 °C is maintained. Generally, this leads to the under-utilization of current fossil-fueled plant capacities, an effect compounded by the prioritization of short-term goals over long-term targets. In the worst case, capacities with a combined value of up to 200 billion € corresponding to 260 GW total capacity may end up stranded by 2035, with significant shares in the coal and gas sectors. In contrast, in the baseline scenario featuring perfect foresight, this amount can be reduced by as much as 75%.

### 1.5.4 Chapter 5: Decarbonizing China's energy system

Growing prosperity among its population and an inherent increasing demand for energy complicates China's target of combating climate change while maintaining its economic growth. This chapter describes potential decarbonization pathways for the electricity, transport, heating, and industrial sectors until 2050. The impact on the transformation of the Chinese energy system is analyzed by applying three different $CO_2$ budget scenarios. The *Paris Agreement* scenario, in line with maximum global warming of 2 °C, is compared to an *Ambitious* (1.5 °C) and a *Limited Effort* (without any budget) scenario. Additionally, the model-based analysis is complemented with an qualitative assessment of current obstacles and barriers that China is facing throughout its energy transformation.

Using an enhanced version of GENeSYS-MOD, with a detailed provincial resolution and an improved temporal representation, allows for the implementation of regional characteristics and disparities within China. Furthermore, the representation of the industrial sector has been updated and extended to allow for specific analyses of the coal consumption in the Chinese energy system.

Results indicate that overall energy system $CO_2$ emissions, and in particular coal usage, have to be reduced drastically to meet (inter-) national climate targets. Specifically, coal consumption has to decrease by around 60% in 2050 compared to 2015. The current NDCs proposed by the Chinese government of peaking emissions in 2030 are, therefore, not sufficient to comply with a global $CO_2$ budget in line with the Paris Agreement. Renewable energies, in particular photovoltaics and onshore wind, profit from decreasing costs and can provide a more sustainable and cheaper energy source. Furthermore, increased stakeholder interactions and incentives are needed to mitigate the resistance of local actors against a low-carbon transformation in China.

### 1.5.5 Chapter 6: Necessity of hydrogen imports for decarbonizing Japan's energy system

With Japan's current plans of establishing a decarbonized and hydrogen-based society by 2050, substantial changes to its energy system need to be made. Due to the limited land availability in Japan, the government is planning to import significant amounts of hydrogen, primarily from Australia (Ministry of Economy, Trade and Industry 2017; COAG Energy Council 2019). In this chapter, a novel stochastic version of the GENeSYS-MOD in conjunction with a full hourly power system dispatch model is used to analyze the impacts of the availability and the price of hydrogen imports on the transformation of the Japanese energy system. Furthermore, the importance of adding elements of uncertainty to energy system modeling is presented and highlighted.

Overall, 9 cases with different hydrogen import prices, ranging from 2 €/kg to 6 €/kg in 2050, have been considered, and one case without the possibility of importing external hydrogen. The prices for hydrogen imports start at a price of 9.5 €/kg in 2019 and are linearly interpolated until the target price in 2050. This analysis does not assess the origin of the imported hydrogen, but it is assumed to come solely from renewable sources. Therefore, the carbon content of the imported hydrogen is assumed to be zero. There is no limit set on the amount of hydrogen imports, such that the model can freely choose the amount of imported hydrogen that would be beneficial from a system optimization perspective.

This analysis highlights that hydrogen can be a valuable resource in certain sectors of the energy system. Importing hydrogen can indeed positively impact energy system developments. However, hydrogen imports are not necessarily required to reach net-zero emissions and the results show that, in all cases, large-scale investments into renewable energy sources need to be made in Japan itself. With large-scale availability of cheap hydrogen, the need for electrification is reduced and thus, the overall power demand increases only about 10% compared to the base year. In contrast, with disabled hydrogen imports, the power demand is doubled (to around 2000 TWh) as large-scale electrification is needed to achieve Japan's ambitious climate goals.

Secondly, this chapter also highlights that using stochasticity in large-scale multi-sectoral energy system models can result in more robust results, especially regarding power system developments. Using stochasticity and uncertainty is advantageous for power system planning, as variable renewable energy sources have an uncertain power generation pattern in reality.

### 1.5.6 Chapter origins and own contributions

Table 1.3 presents the publications of the dissertation's chapters, as well as further information of the own contributions for each chapter.

Table 1.3: Chapter origins.

| Chapter | Pre-publications & Own Contribution |
|---|---|
| 2 | **Designing a Model for the Global Energy System –GENeSYS-MOD** |
| | This chapter is based on: 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. |
| | Joint work with Konstantin Löffler, Karlo Hainsch, Pao-Yu Oei, Claudia Kemfert, and Christian von Hirschhausen. Conceptualization was carried out jointly by all authors. K. L., T. B., K. H., and P.-Y. O. defined the scenarios. Writing of the paper was carried out by K. L., K. H., T. B., P.-Y. O., and C. v. H.. T. B. contributed parts of the model description, technology descriptions, and results. Pre-submission review and proof-reading was handled by all authors jointly. K. L., K. H., and T. B. updated the codebase of OSeMOSYS, including the design and implementation of the transportation and trade blocks. T. B., K. H., K. L., and P.-Y. O. performed the data research. T. B. provided data for heating and transportation technologies, researched and validated the regional potentials, and energy demands. K. L. and T. B. managed the review and editing process. |
| 3 | **Lessons from modeling 100% renewable scenarios using GENeSYS-MOD** |
| | This chapter is based on: P.-Y. Oei et al. 2020. „Lessons from modeling 100% renewable scenarios using GENeSYS-MOD.“ *Economics of Energy & Environmental Policy* 9 (1). https://doi.org/10.5547/2160-5890.9.1.poei. |
| | Joint work with Pao-Yu Oei, Konstantin Löffler, Karlo Hainsch, 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. |

Chapter origins (continued).

| Chapter | Pre-publications & Own Contribution |
|---|---|
| 4 | **Modeling the low-carbon transition of the European energy system** |
| | This chapter is based on: K. Löffler et al. 2019. „Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem.“ *Energy Strategy Reviews* 26:100422. https://doi.org/10.1016/j.esr.2019.100422. |
| | Joint work with Konstantin Löffler, Karlo Hainsch, 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 results and conclusions. Pre-submission review and proof-reading was handled by all authors jointly. K. L., T. B., and K. H. jointly extended the model and carried out the model runs. K. L., T. B., and K. H. jointly carried out the data research process. T. B. and K. L. managed the review and editing process. |
| 5 | **Decarbonizing China's energy system** |
| | This chapter is based on: T. Burandt et al. 2019. „Decarbonizing China's energy system - Modeling the transformation of the electricity, transportation, heat, and industrial sectors.“ *Applied Energy* 255:113820. https://doi.org/10.1016/j.apenergy.2019.113820. |
| | Joint work with Bobby Xiong, Konstantin Löffler, and Pao-Yu Oei. T. B. conceptualized the paper and initiated the research. Scenario definition was carried out jointly by all authors. T. B., B. X., and K. L. wrote the paper jointly. T. B. provided the texts about the introduction, literature review, methodology, results, recommendations, and conclusions. Pre-submission review and proof-reading was handled by all authors jointly. T. B. and K. L. jointly extended the model. T. B. designed and implemented ramping constraints, the time-series reduction algorithm and the industrial sector representation. Model runs were carried out by T. B., B. X., and K. L. T. B., K. L., and B. X. performed the data research. T. B. curated and validated data and model. T. B., K. L., and P.-Y. O. managed the submission and review process. |
| 6 | **Necessity of hydrogen imports for decarbonizing Japan's energy system** |
| | This chapter is based on: T. Burandt. 2021. „Analyzing the necessity of hydrogen imports for net-zero emission scenarios in Japan.“ *Applied Energy* 298:117265. https://doi.org/10.1016/j.apenergy.2021.117265. |
| | Single-author original research article. |

## 1.6 Expansions and enhancements of GENeSYS-MOD

In this dissertation, different versions of GENeSYS-MOD are applied to various case studies. The OSeMOSYS framework is structured in block of functionality. This modular structure allows for dis- or enabling additional features and to change, adjust, and expand existing blocks. Following this modular structure, GENeSYS-MOD has been expanded over the course of my dissertation with various additional features. The key additions and changes utilized in each chapter are presented in Figure 1.7. An overview over the different additions and modifications to GENeSYS-MOD in each model version can be found in Appendix A.1.

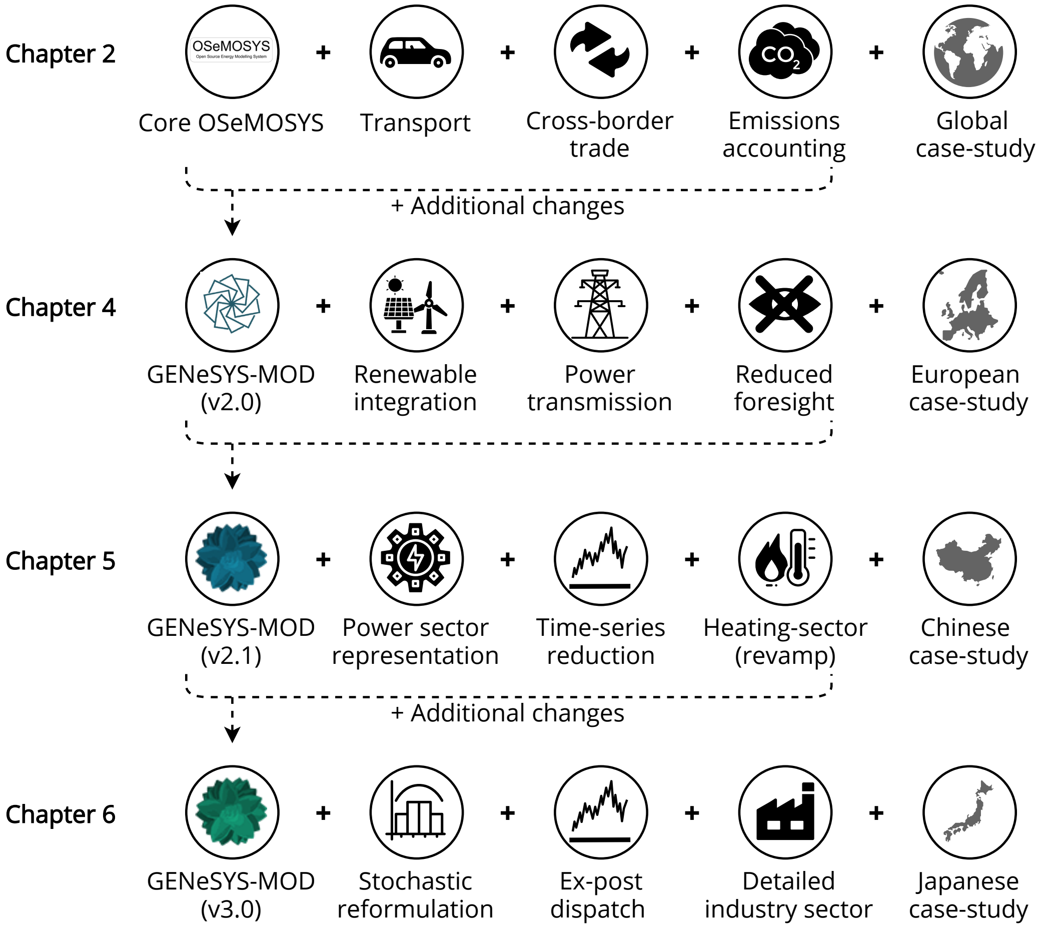

Figure 1.7: Representation of key changes to GENeSYS-MOD utilized in the different chapters.

Firstly, Chapter 2 introduces the first version of GENeSYS-MOD and its changes and additions applied to a Global case study. I.a., equations for modeling modal choice in the transportation sector have been introduced together with cross-border trade of fuels. Furthermore, the accounting of emissions has been changed, and different ways of setting carbon constraints have been introduced.

Secondly, Chapter 4 utilizes GENeSYS-MOD version 2.0 that was further enhanced compared to the version presented in Chapter 2. This version generally features additional constraints regarding the integration of renewable energy sources. The reserve margin constraints have been adjusted to better accommodate for large shares of renewables in the energy system transformation. Additionally, the cross-border transmission of electricity has been replaced by a net-trade formulation of power flows. In this regard, transmission capacities, power losses, and network expansion costs have been introduced to the model. A detailed overview of the model version can found in the data documentation presented by Burandt, Löffler, and Hainsch (2018). In Chapter 3, an additional module to enable reduced/myopic foresight was included in the model. This feature has been used in this Chapter to analyze the stranded assets problem in Europe.

Next, the version of GENeSYS-MOD presented in Chapter 4 has been further expanded within Chapter 5. This new model version model focuses on an improved representation of the power sector, as this sector poses the central link in a decarbonized sector coupled energy systems. In this regard, the implementation of power plants has been changed such that conventional power plants can be dispatched freely and renewable power plants have to curtail their excess power generated. Furthermore, ramping constraints and costs have been added to the model as well. Lastly, for a better depiction of intermittency and variability of renewable energy sources, the time-slice approach utilized in OSeMOSYS was replaced by a time-series reduction algorithm, as presented by Gerbaulet and Lorenz (2017a). In this Chapter, the model is applied to a Chinese case study and also features a more detailed representation of the heating sectors. Especially the industrial heating sector is divided into different process heat temperature ranges and allows for a detailed analysis of coal usage in the Chinese energy system.

Lastly, Chapter 6 further enhances the representation of the non-electricity sectors by changing the model's sectoral structure substantially. Instead of heating demands for buildings, the residential, commercial, and industrial sectors have their own demands for electric appliances, cooling, warm water, and space heating. Also, the implementation of combined heat and power (CHP) plants and district heating (DH) has been improved. Furthermore, the following industrial sub-sectors are now modeled in greater detail: Aluminum, Copper, Ammonia, Chlorine, Steel, Lime, Glass, and Cement production, as well as their primary intermediate products. Also, the model has been reformulated into a stochastic linear program with uncertain demands and renewable generation. Additionally, the results from GENeSYS-MOD are used in a power system dispatch model to assess the general feasibility of the resulting power system for 2050 and to analyze the impact of stochasticity on power sector planning.

The changes to some key areas, such as the representation of the transportation sector or the temporal resolution are presented in the following Subsections.

### 1.6.1 Development of the transport sector in GENeSYS-MOD

Together with the development of the mathematical formulation of the GENeSYS-MOD the underlying database has been substantially enhanced with each major version. In this regard, especially the transportation sector has been enhanced throughout the years. In version 1.0, as utilized in Chapter 2, the aviation and maritime sub-sectors only had limited technology options for decarbonization. Furthermore, BEVs for road-based freight transportation has been omitted together with Plugin-Hybrid Electric Vehicles (PHEVs).

These limitations have been tackled in Model Version 2.0 (Burandt, Löffler, and Hainsch 2018), which has been utilized in Chapters 4 and 5. In this version, PHEVs have been added together with BEVs and Trolley-trucks in the road-based transportation sector. Furthermore, bio-kerosene has been added as an option for decarbonization of the aviation sub-sector.

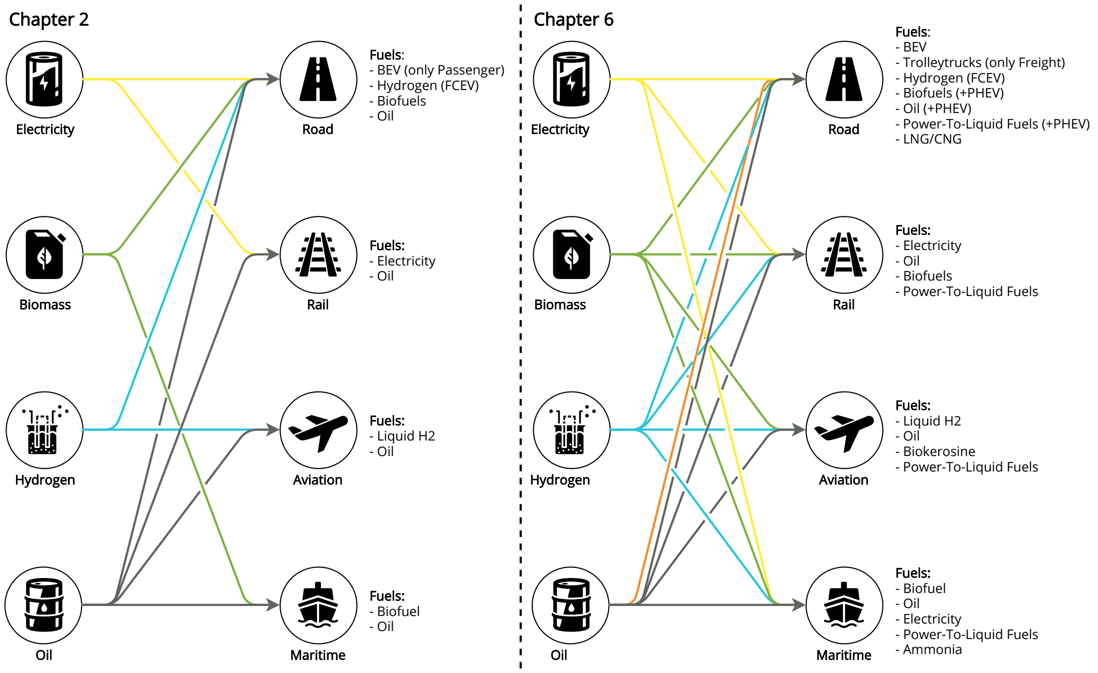

Figure 1.8: Representation of key changes to the transport sector in GENeSYS-MOD comparing Chapter 2 and Chapter 6. Own depiction.

Next, in version 3.0, Power-To-Liquid fuels (based on a Fischer-Tropsch synthesis route with direct-air-capture) have been added for all transportation modes, and additionally, the option for fully electric ships has been integrated as well. The latter is usually disabled and only used for sensitivity analysis and in cases where the option was explicitly enabled within the scenario assumptions. This version has also been used and further enhanced in Chapter 6. Firstly, a distinction between diesel, gasoline, and heavy distillates has been added to the model in this Chapter. Secondly, LNG/CNG as an option for road-based transportation has been included as well. Lastly, ammonia has been included as an option to decarbonize the maritime industry was considered as well. The overall differences between the transportation sector, as included in Chapter 2 and Chapter 6, are presented in Figure 1.8.

### 1.6.2 Temporal representation in GENeSYS-MOD

With each chapter in this dissertation, the temporal specifications of GENeSYS-MOD has been changed to have a better temporal representation of variable renewable energy sources and energy demand. This overall increase in temporal resolution is depicted in Figure 1.9

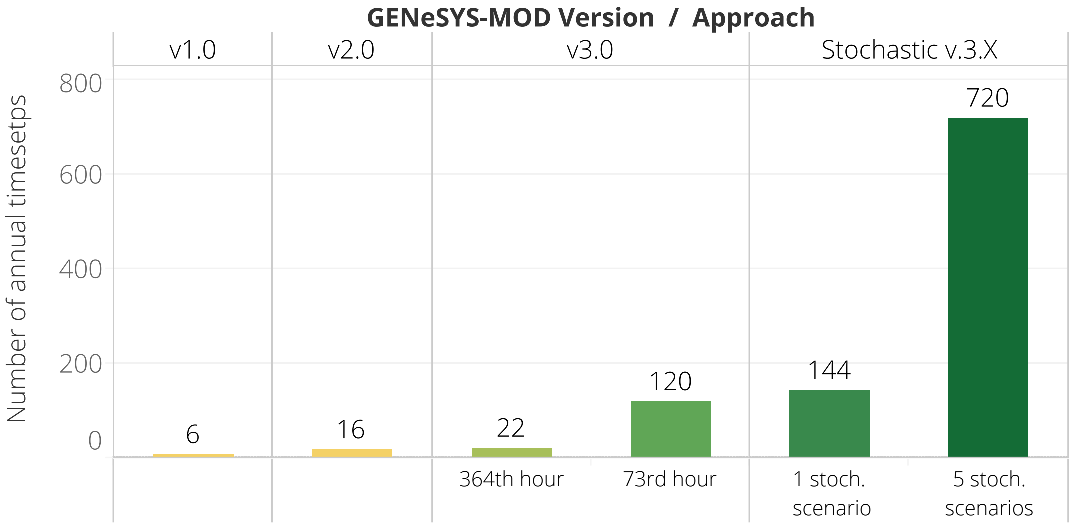

Figure 1.9: Temporal representation of each major model version of GENeSYS-MOD. Own depiction.

In general, the first two versions of GENeSYS-MOD utilized the time-slice approach as presented by the original OSeMOSYS version (Howells et al. 2011). In this regards, the number of time-slices has been increased from 6 in Chapter 2 to 16 in Chapter 4 (also compare (Burandt, Löffler, and Hainsch 2018)). Within Chapter 5, this time-slice approach was replaced by a time-series reduction algorithm, as presented by Gerbaulet and Lorenz (2017a). This new approach increased the number of temporal steps considered in Chapter 5 to 120 time-steps within one year. Next, the temporal structure has been substantially altered in chapter 6. In this new temporal structure, quasi-independent "seasons", each consisting of a consecutive hourly time-series, are grouped together in one stochastic scenario. Energy can only be moved from one season to another via dedicated seasonal storages. Hereby, battery storages can only serve as a short-term storage option for shifting energy within one day. In the case with 5 stochastic scenarios, this new structure resulted in 720 annual time-steps. Although still not having a complete full hourly resolution, Kotzur et al. (2018b) showed that the introduction of different time-layers (*intra* period and *inter* period) together with adjusted storage equations (as done in the stochastic version of GENeSYS-MOD) allows the building of compact temporal energy system models that are still able to consider for the full operational possibilities of long term storages.

## 1.7 Conclusions

Combating climate change and complying with the globally binding targets of the Paris Agreement needs immediate actions throughout all parts of society. Within this dissertation, numerous contributions to the literature of energy systems modeling have been tackling the research questions presented in Section 1.1. Apart from the papers presented in this dissertation, various other studies utilizing GENeSYS-MOD have been successfully published since its initial development in 2017. A selection of additional publications with GENeSYS-MOD that have been co-authored by me and support the primary insights of this dissertation can be found in Appendix A. In general, the following key findings have been obtained using the modeling work and applications to different regional configurations of GENeSYS-MOD:

### 1.7.1 The speed of the energy transformation needs to increase to comply with Paris Agreement targets

As presented in Chapters 4 to 6, considerable investments into of renewable energies need to take place, and fossil energy carriers need to be substantially reduced in order to be able to comply with international and national climate targets. Further additions of conventional generation capacities in Europe, China, or Japan can lead to substantial amounts of stranded assets if climate targets are uphold (see Chapter 4). Comparing the results presented in the global and regional case studies to historical developments from 2015 until 2020, it becomes obvious that the speed of the transformation needs to increase significantly to keep global warming to well below 2 °C as being agreed on by the global community in the Paris Agreement, especially if a large-scale introduction of sector coupling is assumed. This could be observed in all conducted case studies within this dissertation, as well as with other regional applications with GENeSYS-MOD: India (Lawrenz et al. 2018), Germany (Bartholdsen et al. 2019), Mexico (Sarmiento et al. 2019), South Africa (Hanto et al. 2021), and Colombia (Hanto et al. 2019). Overall, decarbonization efforts need to increase substantially and require radical transformation steps. Similar findings are also presented by Bogdanov et al. (2019) and Auer et al. (2020). The recent announcement of net-zero emission targets by i.a., the EU, China, and Japan is a step in the right direction. However, climate targets should not only be announced but also uphold. Thus, policymakers should reconsider their positions regarding fossil fuels. Similarly, nuclear power, given its external costs (Sovacool 2010) as well as its historical and current cost overruns (Haas, Thomas, and Ajanovic 2019; Wealer et al. 2019) is not a cost-optimal solution to reduce $CO_2$ emissions. Instead, policy should further promote renewable energies such as solar PV or wind. Furthermore, the necessity of large-scale decarbonization should be acknowledged by energy system modelers. Hence, the discussion should move away from the general feasibility of, e.g., 100% renewable scenarios, towards the steps that are necessary for the holistic transformation of the energy system.

### 1.7.2 For a successful decarbonization of the energy system, a multi sectoral perspective is key

Sector coupling, especially regarding hydrogen production from electrolysis and electrification of non-electricity sectors, has a major impact on the development of future energy systems. Chapters 2 to 6 present the importance of sector coupling for the transformation of energy systems. Instead of using sector coupling solely as a further option for providing balancing capabilities and flexibility options in the power system, modelers and policy and decision makers should also consider other effects. In this regard, for the decarbonization of non-electricity sectors, either direct electrification, hydrogen applications, or biomass utilization pose the only options. However, sustainable biomass is also limited in its availability, and hydrogen production from renewables is more inefficient than directly using electricity. Thus, hydrogen is mainly used in sectors that are difficult to decarbonize through direct electrification (e.g., high-temperature process heat) instead of a widespread application in the power sector (compare Chapter 6). In general, sector coupling will substantially increase final electricity demand, a fact often neglected in power sector only studies (see Chapter 5). Furthermore, the limited availability of sustainable biomass often constrains the utilization of biomass in the power sector. In this regard, biomass often poses to be more valuable to decarbonize in non-electricity sectors (see also Löffler et al. (2018), Burandt, Crespo del Granado, and Egging-Bratseth (2020), and Hainsch et al. (2021)). Still, as the power sector is key for decarbonization, increased efforts to represent this sector's specifics are needed by energy system modelers. Thus, GENeSYS-MOD has been consequently updated in this regard (See Section 1.6 as well as Chapters 3, 5, and 6) and future plans for an even better representation of power system characterizations exist (see Section 1.8.2). Overall, single-sector analyses and targets can paint a wrong picture about the actual challenge to decarbonize the energy system. Therefore, policy- and decision makers, as well as energy system modelers should consider holistic analyses instead of focusing on single-sector case studies.

### 1.7.3 For a successful decarbonization of the energy system, the power sector needs to be decarbonized first

In sector-coupled energy systems, the power sector will play the key role as it will provide energy either for direct use in non-electricity sectors or for the generation of hydrogen and synthetic fuels. In all analyses presented in this dissertation, the power sector was decarbonized first. Only cheap and largely available renewable energy sources provide the basis for cost-efficient hydrogen production and electrification of the heat, transport, and industrial sectors. Especially in light of the radical steps needed for decarbonization of all sectors (compare Section 1.7.1), ambitious actions in the power system are needed. The sooner the power sector is decarbonized, the sooner a widespread application of highly efficient electrification technologies (e.g., BEVs, heat pumps, electric arc furnaces) can reduce carbon emissions. However, electrification efforts to comply with international climate targets will substantially increase the final power demand, which is depicted throughout this dissertation. As presented in Chapters 5 and 6, net-zero emission pledges and pathways compatible with maximal global warming of 1.5 °C increases electricity demands by 100% (Chapters 6 - Japan) to 400% (Chapters 5 - China). Thus, energy system modelers should consider either multi-sectoral analyses or focus on more ambitious scenarios regarding power system developments to provide meaningful insights. Furthermore, policy- and decision makers should aim to increase decarbonization efforts, especially in the power sector.

### 1.7.4 A decarbonization of the energy system requires a global context, but regional solutions

Each region has its own characteristics and challenges, be it limited space availability, aging power plant parks, high shares of energy-intense industry, central-planner perspective, or regulatory-capture-driven politics. In this dissertation, in all the regional analyses, a decarbonization of the energy system seems feasible given the underlying data and assumptions, and is necessary to comply with international climate targets. In this regard, imports of energy-carriers (e.g., hydrogen) have not been necessarily needed for a transformation of the regional energy system. Nonetheless, Chapter 6 presents that hydrogen imports from outside the modeled region are indeed beneficial from a system optimization perspective. Overall, analyzing energy system transformation pathways on a smaller regional scale bears different insights than a global perspective (see Chapters 3 and 4). However, looking only at a smaller-scale regional perspective while allowing external fossil or renewable energy imports significantly alters the results. In contrast, using larger-scale regional aggregations can lead to underrepresented regional specifications, such as power grid infrastructure, locations of renewable energies, or possibilities for heating networks. However, climate change is both a regional, as well as global challenge. Especially assuming the global carbon budget for specific regions is difficult. Oftentimes, different key indicators are used (e.g., GDP, current emissions per capita, population) to exogenously allocate the carbon budgets to a region (see Chapters 4, 5, and 6 as well as Hainsch et al. (2021)). Only a global perspective would allow to endogenize carbon budget allocations (see Section 1.8.5). Thus, energy system modelers should always reflect on their regional studies in the context of *global* warming. In general, climate change is a global issue and thus policy- and decision makers should aim for further international coordination.

## 1.8 Research Outlook

Although various additions, extensions, and applications of GENeSYS-MOD are presented in this dissertation to generate insights for regional and global multi-sectoral energy system modeling, scientific research will never reach a *finished* state. Therefore, numerous possibilities for further research exists which are presented in the following Sections.

### 1.8.1 Continuous improvement of data and assumptions

Within my Ph.D. studies, I had to review various manuscripts for scientific journals. Using 2010 or earlier base years, outdated cost assumptions, and ignoring current political developments have been some of the problems I had to criticize in part of these reviewed studies. Constantly reflecting, questioning, and improving data, assumptions, and model features are key for providing meaningful and relevant insights. With the current pace of decreasing costs for renewables and battery storage technologies, updating the cost database is essential, especially for cost-optimizing energy system models (which most energy systems belong to, see Section 1.4.2). Increasing the base year for long-term model runs (e.g., as being presented in Chapter 6) is similarly as crucial as using recent cost data. Additionally, availabilities of certain technologies should be evaluated and eventually included in the model (i.e., breakthrough technologies that are currently being researched but may become available in the next years). In this regard, I would like to update certain regional case studies (e.g., Chapter 5) with new data and current political developments and targets. This allows for putting the previously generated results into retrospective and further assessing what developments and in which sectors have not happened in reality and how this affects the overall challenge of a low-carbon transformation in the energy system.

### 1.8.2 Technical representation of power system features

As presented in Section 1.7.3, the power sector is key within multi-sectoral models, as sector coupling generally links other sectors to the power sector. Thus, I want to further improve on the representation of the power system within GENeSYS-MOD. Further research should aim to represent part-load efficiencies and additional reserve and balancing constraints, and their impact on power system planning and sector coupling deployment should be analyzed. Especially within the utilization of time-slices (Chapter 4) or reduced time-series (Chapter 5) as presented in GENeSYS-MOD, peaking requirements and time periods without wind and solar (i.e., *Dunkelflaute*) are often underrepresented. Using a full hourly time series could potentially address this problem. This would also increase the computational requirements and seem hardly possible without decreasing the detail of non-electricity sectors. Instead, potentially peak-capacity constraints and other ways to approximate renewable energies' variability and intermittency should be explored. Rather than using an algorithm to create reduced hourly time series, as presented in Chapter 5, representative time series could be used. Thus, also various clustering algorithms for choosing type-days or type-hours can be used for creating time-series can be explored. In this regard, the effect of the choice of cluster size or clustering algorithm on power system planning and sector coupling should be analyzed. Also, choosing different levels of aggregation of time-series for different sector (e.g., hourly for power and space heating, daily for warmwater, seasonal for gas, yearly for steel) can increase the representation of sectors where an hourly representation is needed and consequently reduce the computational requirements for representing non-electricity sectors.

### 1.8.3 Uncertainties in energy systems

As shown in Chapter 6, modeling uncertainty as stochastic processes can potentially improve the representation of intermittent and variable renewable energies within reduced time series. On the one hand, further research regarding the effects of operational uncertainty is intended. Hereby, choosing different ways of generating stochastic scenarios and the impact of energy system transformation pathways is a possible way to extend the knowledge about the role of stochasticity in long-term energy system planning. Furthermore, instead of just modeling the uncertainty of variable renewable generation, as presented in Chapter 6, the stochasticity of unplanned outages of conventional power plants can also be included to improve the power sector representation. On the other hand, the inclusion of strategic uncertainty should be researched. The availability and potential costs of certain breakthrough technologies (e.g., molten steel electrolysis for steel making) can substantially impact energy system planning. Moreover, long-term demand developments can be represented as strategic uncertainty. In general, (uncertain) demand development is one of the most influential factors in energy systems modeling besides cost developments.

### 1.8.4 Macroeconomic aspects of the energy transformation

Further research should look into the topic of demand development and other macroeconomic factors specifically. As mentioned previously, this could be done via including demand as strategic uncertainly. On the other hand, macroeconomic models exist that specifically analyze the development of GDP, population growth, and economic shocks on the future demand development. In this regard, in conjunction with techno-economic energy system models, macroeconomic models can further elaborate on the effect the energy system transformation has on the global and regional economies. Although an integrated analysis might not be possible due to current computational limitations, linking different model types also shows promising results. In the same context, linking GENeSYS-MOD with resource market models for fossil fuels, but also hydrogen, can generate further insights. Especially the impacts of the available quantities and prices of imported hydrogen for energy system transformation pathways can be assessed within such linked models.

### 1.8.5 Reflecting on global issues

After conducting several detailed regional case studies, I think it is also essential to reflect on their developments within a global context. Climate change and the goal of reducing GHG emissions are global issues and therefore require global attention. However, solutions and mechanisms always need to be implemented on a smaller scale (i.e., countries). The existing regional case studies with GENeSYS-MOD pose an excellent starting point for calculating new global scenarios. In this regard, further research should, on the one hand, aim to increase the level of detail and representation of specific regions within a global context as much as computational resources allow. For example, this would endogenize carbon budget allocations in GENeSYS-MOD and would allow for analyzing fuel exports and imports on a global scale without using specialized market models.

On the other hand, if computational resources prohibit an extensive global case study, the possibility of linking a global model based on aggregated regions (compare Chapter 1) with detailed regional studies should also be explored. This method would still not allow for complete endogenous carbon budget allocations, but could preserve regional characteristics in a global context. In all cases, providing an open source energy system model with a completely open and detailed data set for the global energy system would contribute substantially to the scientific community.

### 1.8.6 Improved openness of the model

GENeSYS-MOD's mathematical formulation and source code are publicly available together with it's data sets. Nevertheless, one significant caveat still exists: As of now, GENeSYS-MOD utilizes commercial solvers and is written in GAMS, which is a closed source and pricey commercial algebraic modeling language. Although GAMS is still prevalent in many companies, modern programming languages such as Python or Julia are much more accessible and thus slowly become the tools of choice not only for the scientific community, but also in companies. Porting the source code to Python or Julia would make GENeSYS-MOD available for a broader audience. This change in programming language also allows the integration of open source and freely available data handling routines (e.g., pandas[19]) directly to the model setup routines. Overall, using a proper programming language over the algebraic modeling language GAMS would increase usability and increase flexibility for adding new features to the model and overall adaptability. In the same context, the model setup, performance, and matrix size of GENeSYS-MOD should be constantly improved to add additional elements to the model without substantially increasing the computational requirements.

Furthermore, each case study usually works with a specific version of GENeSYS-MOD, which is not always compatible with the newest version. Following Sections 1.8.1 and 1.8.5, an update to the old data files such that they work with the current version of GENeSYS-MOD should be pursued. In this regard, when porting GENeSYS-MOD to a more flexible programming language than GAMS, automatic routines for handling outdated data and compatibility issues in general, should be implemented. In most cases, newer versions of the model should generally run with existing data sets, despite maybe not all additional model features would be activated.

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[19] See https://pandas.pydata.org/; last accessed 04.04.2021.

# Part I

# THE GLOBAL ENERGY SYSTEM MODEL

# Chapter 2

# Designing a model for the Global energy system – GENeSYS-MOD

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This chapter is based on joint work with Konstantin Löffler, Karlo Hainsch, Pao-Yu Oei, Claudia Kemfert, and Christian von Hirschhausen published in *Energies* 10 (10) under the title: ”Designing a Model for the Global Energy System – GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS)”.

## 2.1 Introduction

Energy system modeling is an important tool to inform the scientific debate and the policy discussion about different pathways available to reach certain objectives, such as environmental objectives in terms of greenhouse gas emissions. Energy system models have been around for about five decades, inspired by the combination of computer capacities and an increased interest in energy issues in the wake of the first oil crisis (1973); since then, one observes a rapid increase in the number of models and the complexity thereof (Connolly et al. 2010).

In general, energy system models can be classified into two different classes of models: techno-economic, also called process-orientated or bottom-up models, and macroeconomic models (Herbst et al. 2012). While the former can offer a respectable amount of resolution analyzing the impact of specific technologies for their respective energy system, they lack in depicting relevant macroeconomic coherence. Techno-economic energy system models saw a rise in the early 1970s after the first oil crisis to analyze the possibilities of more efficient final energy use (Herbst et al. 2012). Since then, the focus shifted towards a more long-term approach to identify challenges and developments in the broader picture of climate change (Bhattacharyya and Timilsina 2010). Some of today's most known techno-economic models are from the MARKAL/TIMES family of models, e.g., NEMS, PRIMES, or MESSAGE. While some of these models were originally developed as pure optimization models, they already try to bridge the gap between techno-economic and macroeconomic models (EIA 2009; IIASA 2013; E3MLab 2018). These partial equilibrium models commonly focus on energy demand and supply markets, allowing for a broader representation of technological aspects than purely macroeconomic models.

Taking a rather top-down perspective, computable general equilibrium models (CGE) assume a certain market structure, and dynamic of the economy, e.g., competitive or oligopolistic, and then add a certain level of technological detail. Thus, the Emission Prediction and Policy Analysis (EPPA) -model of Massachusetts Institute of Technology (MIT) is a CGE-model assuming a competitive economy and covering a high level of sectoral and macroeconomic detail (Yang et al. 1996).

Adopting a more pragmatic approach, simulation models are designed to replicate the functioning of specific energy markets, without being bound to some predefined, theoretical structural form. Two examples of such simulation models are the World Energy Model (WEM)[1] used by the International Energy Agency (IEA), amongst others to calculate scenarios for the World Energy Outlook (WEO), and Prospective Outlook on Long-term Energy

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[1] for more information see: http://www.worldenergyoutlook.org/weomodel/

Systems (POLES), developed by the University of Grenoble (France), used extensively by the European Commission for long-term scenario work (Criqui 1996). A simple form of simulation models consists of the accounting framework models (Mundaca and Neij 2009). The long-range energy alternatives planning model (LEAP), developed by the Stockholm Environment Institute, belongs to this group. In fact, a link between OSeMOSYS and LEAP is established to extend the existing accounting framework (Heaps 2008).

While the choice of the model structure is a very important issue, the choice of technical detail and assumptions is another driver. For example, results of an energy model will largely diverge depending on whether sector coupling is possible or not, whether certain technologies are available or not, and whether price developments are properly anticipated. In that respect, one observes a critical moment in energy system modeling of low-carbon futures, driven by the unexpected cost decrease of renewable energies and storage technologies. Traditionally, energy system models relied on the trio of fossil fuels with carbon capture, nuclear energy, and renewables; the two former ones providing backup capacity in case of no wind and no sun. This pattern is now challenged by the availability of low-cost storage technologies and other flexibility options (such as demand-side management, high-voltage grid interconnections, etc.), providing the necessary flexibility to balance intermittent renewables (Gerbaulet and Lorenz 2017b). The recent controversy about renewables-based energy scenarios highlights this issue, see Clack et al. (2017) and Jacobson, Delucchi, Cameron, et al. (2017).

This paper contributes to the debate by presenting a new energy system model with a high level of sectoral detail that can be used—among others—for global climate policy scenarios. The model, called GENeSYS-MOD, is a full-fledged energy system originally based on the Open Source Energy Modeling System (OSeMOSYS). The model uses a system of linear equations of the energy system to search for lowest-cost solutions for a secure energy supply, given externally defined constraints on greenhouse-gas (GHG) emissions. In particular, it takes into account increasing interdependencies between traditionally segregated sectors, e.g., electricity, transportation, and heating. OSeMOSYS itself is used in a variety of research to provide insights about regional energy systems and their transition towards renewable energies ((Moura and Howells 2015) implemented a version called SAMBA, where the South American energy system is depicted. Others like (Rogan et al. 2014) tackle national energy system, in this case analyzing the Irish one over the period 2009–2020. Recently, (Lyseng et al. 2016) modeled the Alberta power system, analyzing the impact of carbon prices, loads and costs getting a solution of how a decarbonization until 2030 can be achieved). We provide a translation of the initial model, written in GNU MathProg (GMPL), into the widely used and available GAMS software. We also extended the code and implemented additional functionalities, e.g., a modal split for the transportation sector or relative investment limits for the single model periods. Last but not least, both the code and the data used by GENeSYS-MOD are open-access and freely available to the scientific community.

The paper is structured in the following way: the next section lays out the model and its various aspects. Section 3 presents the model implementation, and its global application. Fuels and technologies, as well as their availabilities and limitations are described. Section 4 presents the results, and Section 5 concludes.

## 2.2 GENeSYS-MOD: Model Description

GENeSYS-MOD has been developed by our team based on the OSeMOSYS, originally coded in GNU MathProg. In addition to a full-fledged conversion of the current version of OSeMOSYS into the GAMS software, we have extended the model significantly. This section describes both the basic structure we have taken over, as well as the additions; we also provide the framework for the application to the global energy system.

GENeSYS-MOD is based on the version of OSeMOSYS created by Noble (2012), has been updated to the newest version of OSeMOSYS, and will be regularly updated from there. GENeSYS-MOD uses the CPLEX-solver (version 12.7.1.0) for its calculations. Just like OSeMOSYS, GENeSYS-MOD consists of multiple blocks of functionality (see Figure 2.1), which work as separate entities that can be changed or extended. To soften the limitations of a linear model, we implemented an additional block, called 'Transportation', implementing a modal split for the distribution of passenger or freight kilometers of a particular type of transportation (e.g., passenger road traffic). Additionally, we added trade costs, losses and capacities for fuels between regions, changed the endogenous calculation of storages, and reformulated the renewable energy target equations. A list of all sets, as well as all relevant parameters, can be found in Appendix B.1.

The model calculates the optimal flows of energy carriers, services, or their proxies that are produced in the production sector, and converted through a network of transformation technologies to meet the set demands (energy carrier proxies are an abstract kind of energy carriers (e.g., passenger kilometers).

To achieve this, the model distinguishes between *fuels* and *technologies*. Energy carriers and services are called *fuels* in the model and hence are referred like this from this point on. Each *fuel* represents a specific energy carrier, a group of similar ones or their proxies. Furthermore, *fuels* are produced, transformed and used by *technologies*. Additionally,

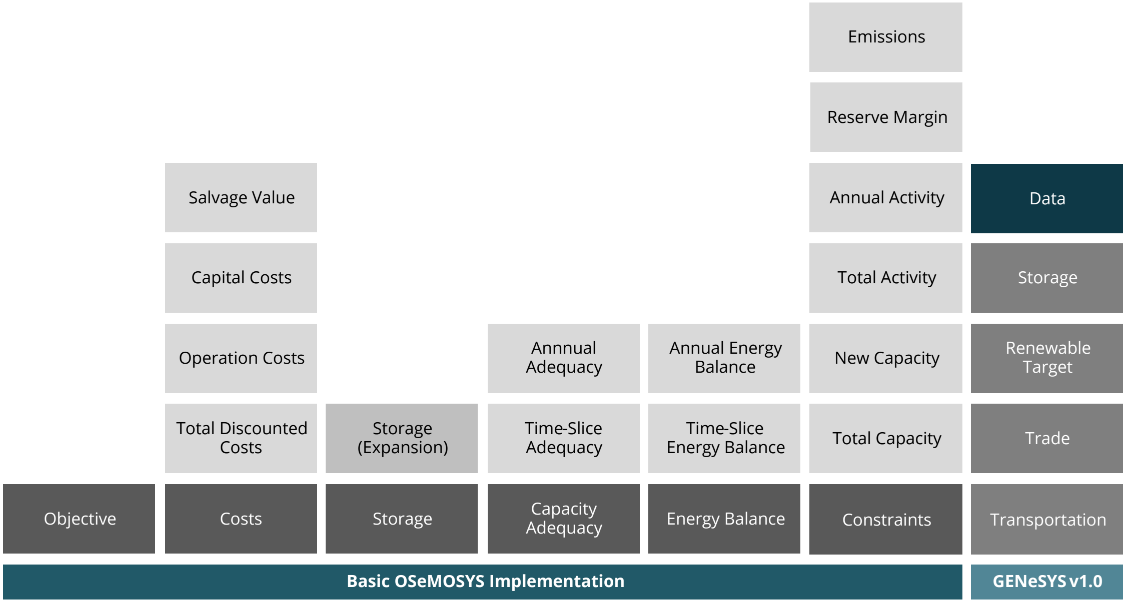

Figure 2.1: Blocks of functionality of GENeSYS-MOD. Own depiction based on Howells et al. (2011).

*technologies* represent all kinds of energy using, producing or transforming techniques (e.g., plants, storages or residual fuel users).

The *technologies* can run in different modes of operation if applicable, e.g., a plant can be defined to produce either electric power in one mode of operation, or heat in the other one. To simulate the loss of energy when converting certain *fuels* into another type, *technologies* have a defined *InputActivityRatio* and *OutputActivityRatio*. *Technologies* with only one of these ratios defined are either supply or demand nodes.

### 2.2.1 Objective function

The objective function minimizes the net present cost of an energy system to meet the given demands for energy carriers and services. This is done by summing up the total discounted costs of each *technology* ($t$) in each *year* ($y$) and *region* ($r$). Furthermore, the total discounted trade costs of importing *fuels* in each *region* are summed up and added to the objective value:

$$\min z = \sum_r \sum_t \sum_y \mathit{TotalDiscountedCost}_{r,t,y} + \sum_r \sum_y \mathit{TotalDiscountedTradeCosts}_{r,y} \tag{2.1}$$

### 2.2.2 Costs

Costs incur when building new capacities of technologies (DiscountedCapitalInvestmenty,r,t), maintaining capacities or using them ($\mathit{DiscountedOperatingCostt}_{y,r,t}$) (see 2.2):

$$\begin{aligned}\mathit{DiscountedOperatingCost}_{y,r,t} = {} & \mathit{DiscountedOperatingCost}_{r,t,y} \\ & + \mathit{DiscountedCapitalInvestment}_{r,t,y} \\ & + \mathit{DiscountedTechnologyEmissionsPenalty}_{r,t,y} \\ & - \mathit{DiscountedSalvageValue}_{r,t,y} \qquad \forall r,t,y\end{aligned} \tag{2.2}$$

These parameters are defined for each *year*, *technology*, and *region* in the model. The operation of and investment in a non-storage *technology* is specified by three kinds of costs. First, a *technology* has a given capital cost. These costs are calculated on an annual basis and are determined by the level of new installed capacity by a per-unit cost to determine the capital investment into new capacities. Furthermore, GENeSYS-MOD uses salvage costs to calculate the salvage value of *technologies* that have exceeded their operational life or are being replaced. Thus, the salvage value is determined by the year of installment, the operational life and a globally defined discount rate. OSeMOSYS offers an implementation of a sinking fund deprecation method and a straight-line depreciation method (the sinking fund deprecation method is an advanced deprecation method in which the estimated salvage value from the deprecation is invested into a fund and the resulting discounted values are used to calculate further salvage rates; the straight-line deprecation method is a simple, linear deprecation method, allocating the same amount or percentage of an asset's cost to each *year*), our model assumes the sinking fund deprecation method as default. Lastly, there are operational costs for each *technology*, divided in variable and fixed costs. Furthermore, the total annual operating costs are discounted back with a globally defined discount rate to the first year modeled to make costs comparable. A global discount rate of 5% was assumed for the calculations of our model. The emission penalty can be determined exogenously (e.g., a given carbon prices), or endogenously (by determining the shadow price resulting from the $CO_2$-emission constraints). The discounted operating costs are then summed up with the discounted capital investment, emissions penalty, and salvage value.

### 2.2.3 Storage

The current implementation of storages in OSeMOSYS is based on general storage assumptions described by Welsch et al. (2012). This implementation has been changed in order to facilitate an endogenous calculation of storage capacities. Instead of setting a *StorageMaxChargeRate*, an Energy-Power-Ratio has been implemented for storages, with the maximum storage capacity being a variable instead. Different types of storage have different operation lifetimes, maximal and minimal ratios, and costs. The model calculates the cost of investments per unit of storage capacity and combines it with the salvage value that is computed for the end of the modeling period. Both costs are used to incorporate the storage equations into the objective function. Equations 2.3 and 2.4 define the rates for charging and discharging for each time slice:

$$\begin{aligned}\mathit{RateOfStorageCharge}_{ld,lh,ls,r,s,y} = \sum_{l}\sum_{m}\sum_{t}(&\mathit{RateOfActivity}_{l,m,r,t,y}\\ &\cdot \mathit{TechnologyToStorage}_{m,r,s,t}\\ &\cdot \mathit{Conversionls}_{l,ls}\\ &\cdot \mathit{Conversionld}_{l,ld}\\ &\cdot \mathit{Conversionlh}_{l,lh}) \qquad \forall ld, lh, ls, r, s, y \qquad (2.3)\end{aligned}$$

$$\begin{aligned}\mathit{RateOfStorageDischarge}_{ld,lh,ls,r,s,y} = \sum_{l}\sum_{m}\sum_{t}(&\mathit{RateOfActivity}_{l,m,r,t,y}\\ &\cdot \mathit{TechnologyFromStorage}_{m,r,s,t}\\ &\cdot \mathit{Conversionls}_{l,ls}\\ &\cdot \mathit{Conversionld}_{l,ld}\\ &\cdot \mathit{Conversionlh}_{l,lh}) \qquad \forall ld, lh, ls, r, s, y \qquad (2.4)\end{aligned}$$

### 2.2.4 Transportation

The 'Transportation' block introduces a modal split for transportation *technologies*. First, the demand of a certain *fuel* is split by the defined modal types into several demands per *modal type*. Furthermore, *technologies* can be tagged with *modal types* to define which *technology* can cover this split demand. Lastly, the tagged *technologies* must produce at least the amount of the split demand:

$$\begin{aligned}\mathit{DemandSplitByModalType}_{f,mt,r,y} = {} & \mathit{AccumulatedAnnualDemand}_{f,r,y} \\ & \cdot \mathit{ModalSplitByFuelAndModalType}_{f,mt,r,y} \; \forall f, mt, r, y \end{aligned} \tag{2.5}$$

$$\begin{aligned}\mathit{ProductionSplitByModalType}_{f,mt,r,y} = \sum_t & (\mathit{TagTechnologyToModalType}_{mt,t} \\ & \cdot \sum_l \mathit{RateOfProductionByTechnology}_{f,mt,r,y} \\ & \cdot \mathit{YearSplit}_{t,y})) \qquad \forall f, mt, r, y \end{aligned} \tag{2.6}$$

$$\mathit{ProductionSplitByModalType}_{f,mt,r,y} \leq \mathit{DemandSplitByModalType}_{f,mt,r,y} \quad \forall f, mt, r, y \tag{2.7}$$

### 2.2.5 Trade

To implement trade costs in our model, we had to split the pre-existing trade variable into separate export and import variables. The total trade costs for each *time slice*, *year* and region are then calculated by summing up the trade costs for each *fuel* that is imported into a given region from another region, as seen in Equation 2.8. To incorporate these costs into the objective function, they are furthermore discounted back to the starting year of the model run and then added to the total discounted costs. Also, trade losses, as well as maximum trade capacities for power trade have been implemented in the model equations. Equation 2.9 demonstrates the inclusion of losses that occur on exports, Equation 2.10 presents the maximum capacity constraint for an electricity trade route, which has to be satisfied for all *time slices*:

$$\begin{aligned} \mathit{TotalTradeCosts}_{l,r,y} = \sum_{f}\sum_{rr}(&\mathit{Import}_{f,l,r,rr,y} \\ &\cdot \mathit{TradeRoute}_{f,r,rr,y} \\ &\cdot \mathit{TradeCosts}_{f,r,rr}) \qquad \forall l,r,y \end{aligned} \tag{2.8}$$

$$\begin{aligned} \mathit{NetTrade}_{y,l,f,r} = \sum_{rr}(&\mathit{Export}_{f,l,r,rr,y} \\ &\cdot (1 + \mathit{TradeLossBetweenRegions}_{f,r,rr,y}) \\ &- \mathit{Import}_{y,l,f,r,rr}) \qquad \forall l,r,y,f \end{aligned} \tag{2.9}$$

$$\mathit{TradeCapacity}_{y,Power,r,rr} = \frac{\mathit{Import}_{y,l,Power,r,rr} + \mathit{Export}_{y,l,Power,r,rr}}{\mathit{CapacityToActivityUnit} \cdot \mathit{YearSplit}_{y,l}} \; \forall y,l,r,rr \tag{2.10}$$

## 2.3 Model application and implementation

GENeSYS-MOD includes a multitude of supply and transformation technologies to satisfy the different demand needs that, in combination, form the global energy system. Its possible flows, technologies (symbolized by boxes), and demands (shaded boxes) are illustrated in 2.2

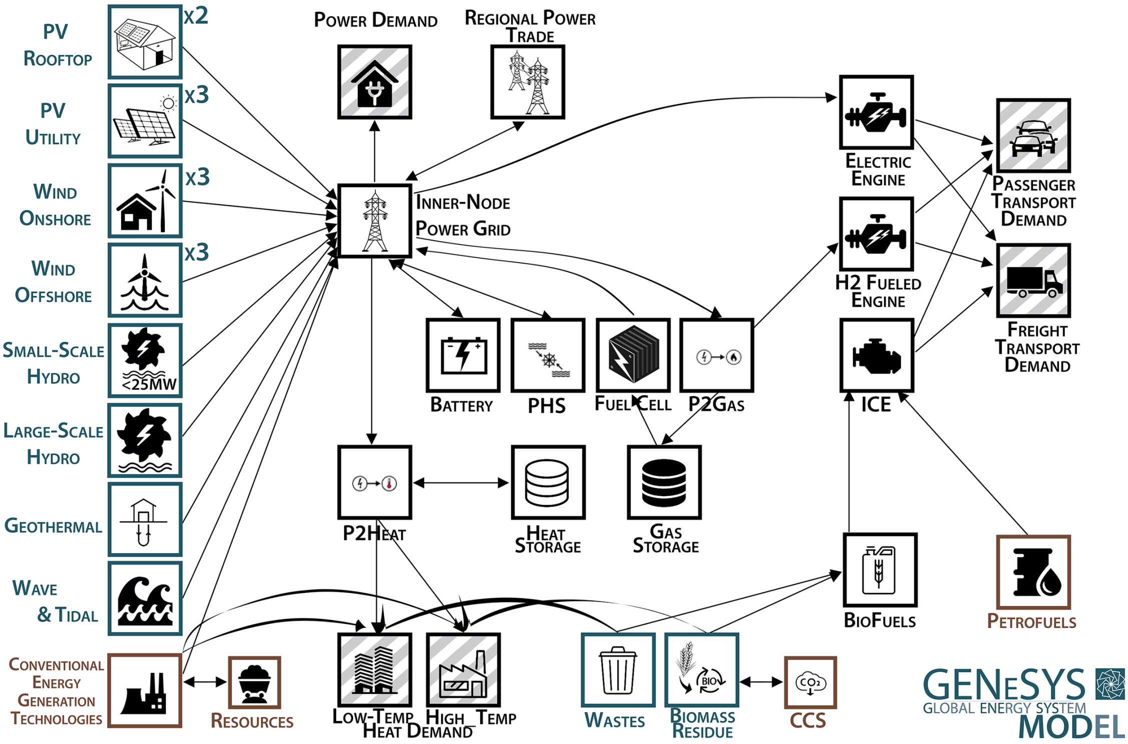

Figure 2.2: Technological and sectoral coverage of GENeSYS-MOD. Own Depiction.

### 2.3.1 Regional Disaggregation and Trade

In its current form, GENeSYS-MOD addresses global energy issues, and for this purpose it splits the world into ten *regions*: Africa, China, Europe, Former Soviet Union, India, Middle East, North America, Oceania, Rest of Asia and South America (see Appendix B.3 for a list of countries in each of the regions). These *regions* represent geographical clusters of countries in which energy is both produced and consumed (see Figure 2.3 for a graphical representation). At the same time, the regions act as nodes connecting with other regions to allow for trading. All parameters, e.g., on demand and production potentials (e.g., such as the potential area in which onshore wind generators could be built), and other parameters such as costs and efficiency are defined for each region. *Regions* are able to trade *fuels* via the set *TradeRoutes*, which define which *regions* are able to trade a certain type of *fuel* with one another. Because of the large distances between *regions*, we disabled the trading of power for our model calculations.

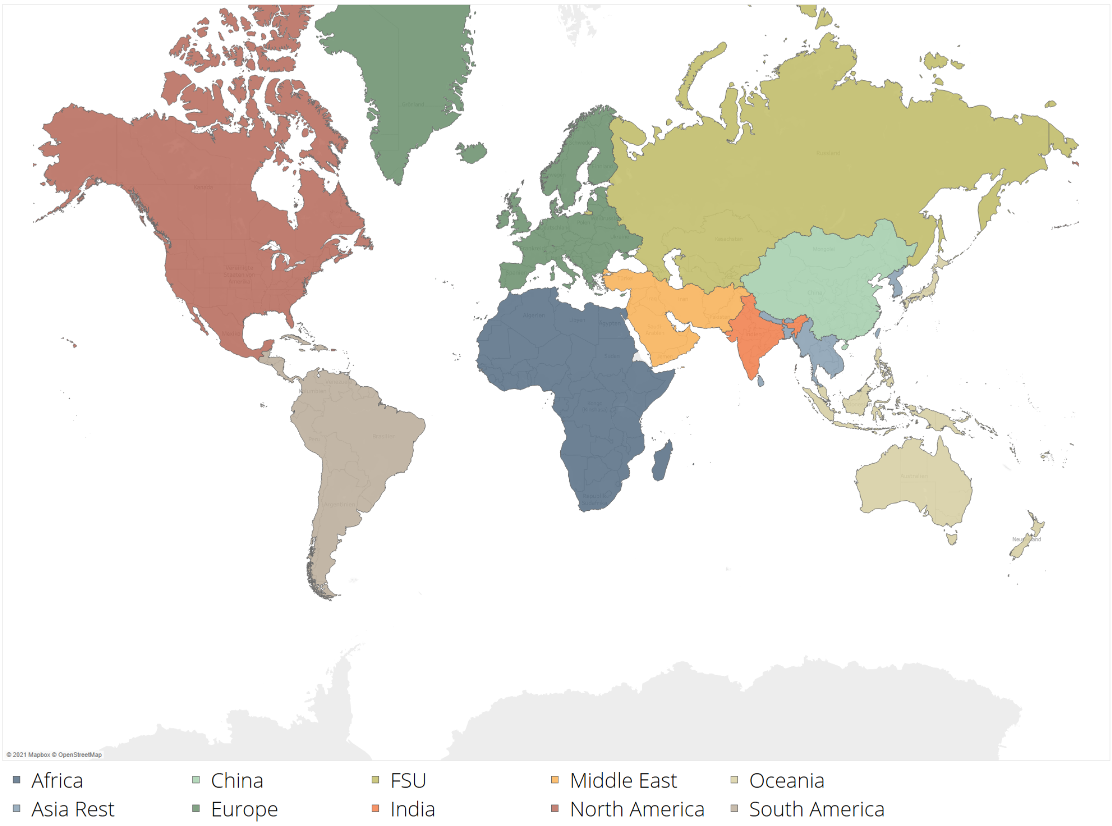

Figure 2.3: Regional disaggregation of GENeSYS-MOD. Own Depiction.

### 2.3.2 Demand and fuel disaggregation

GENeSYS-MOD distinguishes three groups of final demand: electricity, heat, and mobility. They are then split up into low-temperature heat (used for water and room heating and cooling) and high-temperature heat (process heat over 100° C) in the heat sector, and passenger and freight transport demands in the mobility sector. Other *fuels* in the model are used for transformation purposes (e.g., hydrogen or biomass), serve as an input (such as the conventional fossil fuels coal, natural gas, or oil), or are used to define certain technical restrictions. These 'area input fuels' can be used to limit the use of certain *technologies* (such as PV cells) by available suitable land on a regional basis, which may serve as a superior indicator to capacity-based calculations. As such, we defined the following *fuels* for our final demands (see Table 2.1).

Table 2.1: End-use demand fuel disaggregation.

| **Power [in PJ]** | **Heat [in PJ]** | **Mobility** |
|---|---|---|
| Electricty | Low-temperature<br>High-temperature | Passenger [in Gpkm]<br>Freight [in Gtkm] |

### 2.3.3 Modeling period and investment restrictions

The modeling period covers the years 2020 to 2050 in 5-year-steps. The year 2015 is used as base year with existing capacities. There are no fixed investment limits for *technologies*. Instead, we opted for a percentage-based approach in order to reproduce investment rates more realistically. Therefore, the investment is limited by the total amount invested, as well as the maximum capacity potential.

### 2.3.4 Time disaggregation

GENeSYS-MOD presents most results on an annual basis, but it offers a much more disaggregated approach with respect to time periods and time dependent data, such as, for example, the power demand per region or the use of storages. This is accomplished by dividing the year into several *time slices*, which can be defined by the model user to suit the needs of the application. One year is thus divided into seasons, which then contain *day types* (e.g., weekday/weekend) and *daily time brackets* (e.g., day/night), all defined as fractions of a year.

For this model specification, we chose to use three seasons (intermediate, summer, winter —with intermediate combining the seasons of autumn and spring), one *day type*, and two *daily time brackets* (day, night). The *daily time bracket* ”day” is set to $16$ h ($^2/_3$ of one day), while ”night” is 8 h long ($^1/_3$ of one day). Multiplying these fractions for each combination (calculation example: *Summer day* $= 1$*year* $\times\ 1/4$*(season 'summer')* $\times\ 2/3$*daily time bracket 'day'* $= 0$) gives us a total of six different time slices. 2.2 presents the fraction per year for all the time slices used (given in % of one year).

Table 2.2: Time disaggregation (% of one year).

| **Winter Day** | **Winter Night** | **Intermediate Day** | **Intermediate Night** | **Summer Day** | **Summer Night** |
|---|---|---|---|---|---|
| 17% | 8% | 33% | 17% | 17% | 8% |

### 2.3.5 Emissions

GENeSYS-MOD is mainly targeted at greenhouse gas emissions from the energy sector, and therefore monitors $CO_2$ in particular detail. $CO_2$ constraints can be defined at the regional level, but also at the global level. For the applications used in this paper, we choose the global approach with a $CO_2$ budget corresponding to the 1.5–2° C target; according to (IPCC 2015), about 550–1300 Gt $CO_2$ may be emitted between 2011 and 2050. Considering the global emissions between 2011–2014, as well as taking into account non-energy emissions (such as from industry, or land use and land-use change), we opted for a budget of 650 Gt of $CO_2$ for the GENeSYS-MOD global model calculations.

The emission values per energy carrier per petajoule have been calculated, based on Edenhofer et al. (2012) (for nuclear energy production) and EIA (2016) (for coal, gas and oil). All emissions can then be calculated for each technology based on their fuel consumption.

### 2.3.6 Storage

GENeSYS-MOD has been designed with attention to storage requirements, in particular in the electricity sector. Storages are connected on a *technology* basis, meaning each *technology* that wants to store or use stored energy must be connected by defining the link between them. Also, storages do not store specific fuels, but are generic ”energy depots”, whose input is defined by the output *fuel* of the *technology*. A list of all implemented *technologies* and *storagetechnologies* can be found in Appendix B.2.

### 2.3.7 Modal split for transportion

The modal split for the transportation sector is exogenously given, and based on calculations that are based on data from the 450 ppm scenario from the World Energy Outlook (International Energy Agency 2015b), using a regional differentiation. While the modal split is strictly defined for 2015, these bounds are consecutively lowered to let the model find the optimal solution.

### 2.3.8 Input data

This section provides the main data sources required for the subsequent model calculations. As the scenarios focus on low-carbon technologies, particular weight is placed on renewable sources in this section; this will be different when we address other questions using GENeSYS-MOD, e.g., the optimal selection of coal vs. natural gas utilization.

#### 2.3.8.1 Fossil fuel availability and prices

Current energy systems are mainly based on conventional resources like coal, gas, oil, and nuclear power (International Energy Agency 2015b). GENeSYS-MOD can use conventional fuels and their corresponding technologies, and invest into new capacities. Existing capacities of conventional and renewable technologies are considered by the model as residual capacities, and phased out as their lifetime expires (Farfan and Breyer 2017b). The annual production of the conventional energy resources published in the World Energy Outlook (International Energy Agency 2015b) is taken as a constant limit in the model. Carbon capture is not being considered, since it is not commercially available and is unlikely to be so in the future.

#### 2.3.8.2 Renewable technologies and potentials

##### 2.3.8.2.1 Solar

With worldwide average annual growth rates of solar power supply of 46.2% since 1990, solar power it is one of the main drivers of any low-carbon transformation (European Commission 2016b). The technical potential of solar power is very high, but it is highly dependent on regional and temporal circumstances. We consider two different technologies for power generation purposes: photovoltaics (PV) and concentrated solar power (CSP). The former makes use of direct radiation as well as radiation reflected by the clouds, and therefore results in a steadier energy inflow. Similar to Jacobson, Delucchi, Bauer, et al. (2017), we consider residential and commercial photovoltaic panels on the one hand, and utility plants at open areas on the other hand. The potentials of these technologies with respect to different regions are adopted from Jacobson, Delucchi, Bauer, et al. (2017) and illustrated in 2.3. Sites with less than 4 kWh/m$^2$/d are excluded, as are sites with too high slope, urban areas, or protected areas.

Table 2.3: Solar PV - Regional potentials.

| **Region** | **PV-Residential [100km$^2$]** | **PV–Commercial [100 km$^2$]** | **PV–Utility [100 km$^2$]** | **Total [100 km$^2$]** |
|---|---|---|---|---|
| Africa | 42.04 | 23.05 | 105.48 | 170.57 |
| Asia Rest | 36.67 | 26.94 | 29.92 | 93.53 |
| China | 56.06 | 69.59 | 46.94 | 172.59 |
| Europe | 33.42 | 41.60 | 27.63 | 102.65 |
| India | 28.19 | 38.87 | 14.87 | 81.93 |
| Middle East | 23.87 | 17.56 | 35.04 | 76.47 |
| North America | 46.12 | 45.60 | 100.92 | 192.64 |
| Oceania | 8.24 | 13.12 | 42.64 | 64.01 |
| FSU | 8.41 | 11.70 | 100.07 | 120.18 |
| South America | 25.92 | 25.92 | 88.49 | 140.33 |
| Total | 308.92 | 313.98 | 592.01 | 1214.91 |

The conditions for using concentrated solar, on the other hand, are more constraining. CSP requires a high intensity of direct radiation, and produces low efficiency values with lower radiation. We consider sites with more than 2000 kWh/(m$^2\cdot$ year), corresponding to capacity factors of about 20–25% (Trieb et al. 2009). This occurs mainly in regions such as Africa, the Middle East and Oceania.

#### 2.3.8.2.2 Wind

The availability of wind can vary strongly, both during the day but also seasonally, with availabilities up to 50% higher in winter months, e.g., in Europe (Archer and Jacobson 2005). In addition, the availability of wind power can also be constrained by environmental factors, such as the exclusion of high altitude winds (Marvel, Kravitz, and Caldeira 2013). As a result, we only consider locations where the average wind speed in 10 meters height exceeds 4 m/s (Hau 2008).

Our model differentiates between onshore and offshore wind. Onshore wind technology is already reasonably mature compared to other renewable energy sources, with its efficiency being close to the theoretical optimum. Most wind turbine systems have hub heights around 100 meters with rotor diameters of 50–100 m (Schröder et al. 2013). The potentially suitable area for onshore plants is directly given by the calculation of Jacobson, Delucchi, Bauer, et al. (2017). However, the potentially suitable area for offshore plants was calculated by a reverse calculation of the total GW (Gigawatt) potential given by Arent et al. (2017).

Table 2.4: Wind - Regional potentials.

| **Region** | **Wind Onshore [100km$^2$]** | **Wind Offshore [100 km$^2$]** | **Total [100 km$^2$]** |
|---|---|---|---|
| Africa | 125.2 | 1.1 | 126.3 |
| Asia Rest | 41.0 | 2.9 | 43.9 |
| China | 2.3 | 2.1 | 4.4 |
| Europe | 10.9 | 4.2 | 15.1 |
| India | 1.1 | 0.1 | 1.2 |
| Middle East | 27.5 | 0.1 | 27.6 |
| North America | 21.2 | 4.7 | 25.9 |
| Oceania | 9.7 | 5.2 | 14.9 |
| FSU | 10.9 | 2.7 | 13.6 |
| South America | 23.5 | 8.3 | 31.8 |
| Total | 273.3 | 31.4 | 304.7 |

Therefore, we used their assumption of a power density of 5 MW/km$^2$. The latter, in combination with the stated regional potential for wind power in GW, allows the calculation of the possible suitable area, which is shown in 2.4.

#### 2.3.8.2.3 Biofuels

If all possible sources of residues and waste would be used, the world's total technical annual potential is estimated to be more than 100 EJ per year (Sims et al. 2010). Since it is difficult to estimate the regional potential of residues and forest products, we refer to solid biomass waste. This includes renewable urban waste, but also food wastes that are produced at the first stages of the supply chain. Furthermore, we only consider second-generation biomass for energy production. Compared to first-generation energy crops (e.g., wheat, corn, beet or palm oil), they have an important advantage because they are non-food materials. This means that agricultural by-products like cereal straw, sugarcane bagasse, or forest residues are used and biofuels do not compete directly with food production.

The share of food losses and waste (inclusive animal excrements) of the total energetic biomass potential is 42% (Mühlenhoff 2013). Therefore, food losses and waste offer a potential of around 11.7 EJ. Some important differences exist between different regions depending on their grade of industrialization. In highly developed countries like North America or Europe, the annual per capita food loss and waste is 280–300 kg. On the other hand, in less-developed countries, the figure is lower, at 120 and 170 kg (Gustavsson, Ceder-

Table 2.5: Biomass - Regional potentials.

| Region | 2015 [PJ] | 2050 [PJ] |
|---|---|---|
| Africa | 154 | 401 |
| Asia Rest | 192 | 798 |
| China | 713 | 1165 |
| Europe | 504 | 504 |
| India | 170 | 737 |
| Middle East | 371 | 1061 |
| North America | 514 | 633 |
| Oceania | 232 | 232 |
| FSU | 409 | 527 |
| South America | 667 | 1258 |
| Total | 3926 | 7316 |

berg, and Sonesson 2011). In accordance with the IEA (International Energy Agency and Organisation for Economic Co-operation and Development 2016), we assume that 40% of the collected waste could be used for power production. Thus, we calculated different regional potentials based on data from Gustavsson, Cederberg, and Sonesson (2011). Cost assumptions for biomass and their evolution from 2015 to 2050 are adopted from Sims et al. 2010 and Havlík et al. (2011). The resulting potentials are shown in 2.5. Costs are reduced from 14.5 €/GJ in 2015 to 2.2 €/GJ in 2050 due to technical improvements.

#### 2.3.8.2.4 Hydropower

Hydropower is the energy transported by the water on its way from a higher to a lower level, and therefore has the highest density in regions with high slope and a constant supply of water. The greater the amount of water the river transports and the steeper the gradient of its stream course, the higher the potential in this area. Most of hydropower potentials are located in mountainous regions (Edenhofer et al. 2012). The global annual amount of water transported this way is estimated to be 47.000 km$^3$, of which 28.000 km$^3$ is on the surface. This sums up to around 40.000 TWh/year theoretical hydropower generation (Edenhofer et al. 2012). Regions like Asia, especially China, South America, and Africa show the most hydropower resources. Compared to solar and wind, hydropower is more predictable and constant over the years, but there are seasonal fluctuations caused by rain or melting snow. The regional potentials of hydropower are calculated using data from (EIA 2016), (Cleveland and Morris 2013) and are represented in 2.6. For the resulting potentials, an even distribution of small and large-scale hydro has been assumed.

Table 2.6: Hydropower - regional and economical potentials.

| **Region** | **Hydropower (Small) [GW]** | **Hydropower (Large) [GW]** | **Total [GW]** |
|---|---|---|---|
| Africa | 130.0 | 130.8 | 261.6 |
| Asia Rest | 85.0 | 85.0 | 170 |
| China | 185.9 | 185.9 | 371.8 |
| Europe | 129 | 129 | 258 |
| India | 99.2 | 99.2 | 198.4 |
| Middle East | 39.0 | 39.0 | 78 |
| North America | 107.8 | 107.8 | 115.6 |
| Oceania | 42.1 | 42.1 | 84.2 |
| FSU | 121.6 | 121.6 | 243.2 |
| South America | 165.7 | 165.7 | 331.4 |
| Total | 1106.1 | 1106.1 | 2212.2 |

#### 2.3.8.2.5 Geothermal

Geothermal energy can provide a regular supply, but it is relatively expensive compared to other sources, although advances in drilling technologies and more effective reservoir management have been lowering costs significantly in the recent past (Younger 2015). The technical potential of geothermal energy is abundant, and it is broadly available (Rosinski, Coleman, and Cerezo 2010). The geothermal resources are caused by three important components: (i) the energy flow within the Earth crust (magma, water, steam, gases); (ii) the heat flow due to conduction; and (iii) the energy that is stored in rocks and fluids within the earth crust (Stefánsson 2005). The most promising geothermal sources are located near plate margins and geologically active regions. Most of the existing geothermal plants for power plants are located in regions with high-temperatures of the crust surface, high rock permeability, or a naturally existing water-steam resource (Rosinski, Coleman, and Cerezo 2010; Dickson 2003; Rybach 2014).

Some early research projects indicate a high potential of geothermal recourses for the energy sector. (Roberts 1978) stated that within the first three kilometers of the continental earth crust exists sufficient heat to provide sufficient energy for the next 100,000 years. Nevertheless, not all the theoretically existing energy can be used directly in terms of heat or to generate electricity, both for technical and economic reasons. The resulting regional potentials for geothermal power generation, based on Gawell, Reed, and Wright (1999) and Holm et al. (2010) are shown in 2.7.

Table 2.7: Geothermal - Regional potentials.

| Region | Regional potential [GW] |
|---|---|
| Africa | 12.8 |
| Asia Rest | 25.7 |
| China | 3.5 |
| Europe | 6.8 |
| India | 0.6 |
| Middle East | 1.4 |
| North America | 25.4 |
| Oceania | 13.0 |
| FSU | 3.7 |
| South America | 44.9 |
| Total | 137.8 |

#### 2.3.8.2.6 Others

Renewable, synthetically produced gas, such as hydrogen, can be used to provide low and high-temperature heat, as well electric power. Furthermore, liquefied hydrogen gas can be used as fuel in the transportation sector. Thus, hydrogen can play a major role in a low-carbon transformation. Hydrogen gas can be used in combined heat and power plants (CHP) to produce electricity and heat (Henning and Palzer 2012). Renewable hydrogen gas CHPs are modeled according to the characteristics of the natural gas CHP technology, with hydrogen as input instead. Because hydrogen can only be generated by using expensive electrolysis technologies, power and heat generated by hydrogen is rather expensive. In the transportation sector, hydrogen can be used in fuel-cell-driven electric vehicles (FCEV) via gaseous hydrogen. FCEV provide long range services up to 900 km per refueling (International Energy Agency 2015a). However, this long range is achieved through a decreased overall efficiency in comparison to battery-driven electric vehicles. Additionally, other long-range transportation technologies can use liquefied hydrogen, such as freight cargo trucks or aircraft.

### 2.3.9 Cost assumptions

Since the model identifies the least-cost combination for the energy system, cost parameters, especially their assumptions for the future, are crucial and a main driver of the results. Hence, it is essential to understand the relations and implications of those costs and verify results by testing for their sensitivity. The different types of cost considered in GENeSYS-MOD are: (1) cost for building capacities and running those, (2) emission penalties, and (3) costs for trading fuels between regions. Most of our cost assumptions and data originate from Schröder et al. (2013), Gulagi, Bogdanov, and Breyer (2017), and Breyer et al. (2017). Also, price estimates from the 450 ppm scenario of the World Energy Outlook (International Energy Agency 2015b) are taken as fuel prices for fossil fuels in our model. Emission penalties are currently not considered in this model setup, as we opted for a global carbon budget instead. For more information about the different costs consult Burandt et al. (2017). The capex of different electricity generating technologies can be found in Appendix B.4.

## 2.4 Scenario definition and results

### 2.4.1 Scenario definition

GENeSYS-MOD was designed to develop and compare different scenarios for the global energy system, but for our first application, we have chosen a rather simple structure: we are interested in the cost-optimal energy mix that respects a global $CO_2$-target calibrated for a 1.5–2° C world, as explained above: defined here as a $CO_2$-budget of 650 Gt for 2015 to 2050 (consistent with a 1.5° C scenario). All technologies described in the previous section are available. Also, a sensitivity analysis concerning various parameters and assumptions has been made (costs of renewable power generating technologies, storage costs, fossil fuel costs, and demand growth), showing that our results are robust and that the model behaves accordingly.

### 2.4.2 Results

#### 2.4.2.1 The global energy system

Figure 2.4 shows the results for the basic run of GENeSYS-MOD, applied to the global energy system. Our investigation of whether a globally sustainable 100% renewable energy supply is possible by 2050 results in the finding that it is technically and economically feasible, with a resulting shadow price for $CO_2$ of about 32€ per ton $CO_2$. This shows that a switch towards 100% renewables can be achieved with very low costs, as renewable technologies become increasingly competitive.

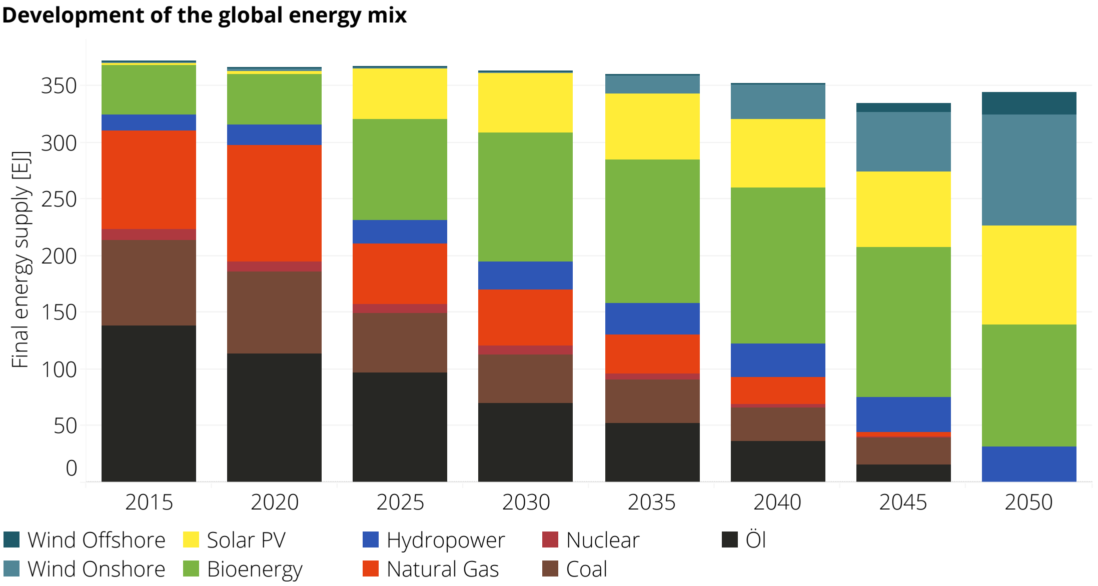

Figure 2.4: Development of the global energy mix (final energy supply) with a $CO_2$-budget of 650 Gt.

The global energy system shifts from a world almost entirely reliant on the fossil fuel sources oil, coal, and natural gas, to a fully decarbonized energy system in 2050. While starting out slowly, the growth of renewables, especially biomass, solar and wind quickly picks up and reaches a stage of about 50% of the energy mix being renewable as soon as 2030. This transformation varies strongly from sector to sector, as well as on a regional basis.

### 2.4.2.2 Electricity

The energy system experiences a very strong sector coupling of the power with both the heat and transportation sectors. This can be observed via the vastly rising generation of power, more than tripling by 2050 compared to 2015 values. Figure 2.5 shows the development of the power generation mix between 2015–2050 at the global level. While conventional sources still account for over 66% of consumption in 2015, and even over 80% when including hydropower, the energy mix changes structurally from 2025 on, mainly due to solar photovoltaics becoming economically competitive. Since low-carbon electricity generation technologies are available at low costs, the electricity sector is the first to decarbonize, and freeing up $CO_2$-emissions for the heat and transportation sectors. Natural gas loses market shares relatively early (2025), and the use of coal is also significantly reduced. Due to possible sunk costs, rising fossil fuel prices (especially for natural gas), and increased competitiveness of renewables, no new fossil-fueled power plants are constructed. Instead, existing capacities are being utilized, depending on their remaining lifetimes. Coal remains the largest fossil fuel source for power generation, although still quickly declining in overall amounts after 2020.

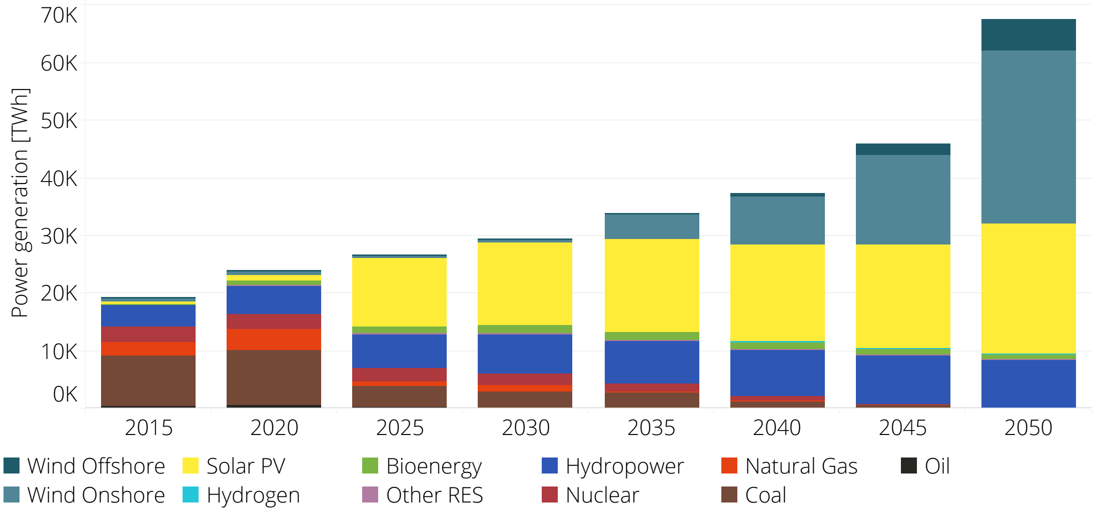

Figure 2.5: Development of global power generation.

Somewhat surprisingly, wind picks up market shares relatively late, i.e., in the 2030s (onshore wind) or even after 2035 for offshore wind. This is due to optimal solar potentials being exhausted, which gives wind power the opportunity to enter the mix. The contribution of hydropower increases slightly, with most optimal potentials already being utilized beforehand. Hydropower makes up a share of about 13% of the final power generation profile. Figure 2.6 presents the regional power generation mixes in 2050, demonstrating regional differences in our model results.

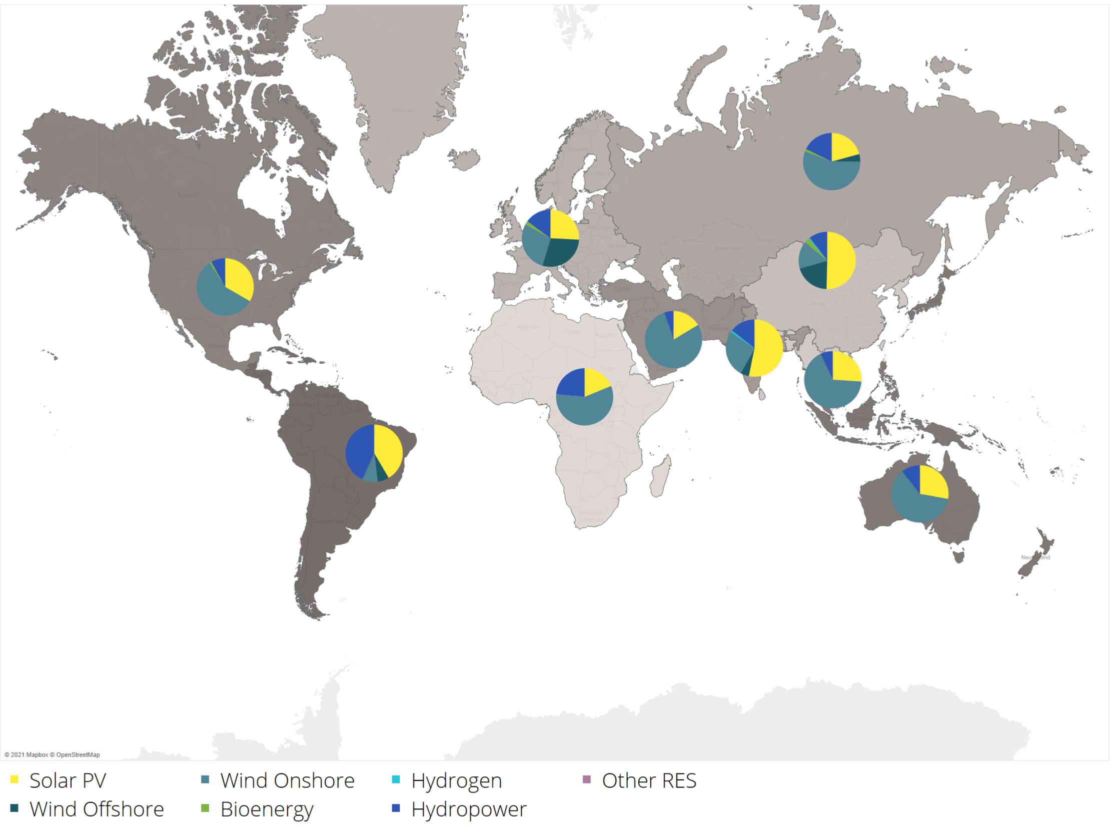

Figure 2.6: Power generation profiles in 2050.

### 2.4.2.3 Heat

The energy mix in the heating sector shows quite a different decarbonization pathway. Figure 2.7 shows the model results for the high-temperature heat production from 2015–2050. After a first expansion of natural gas, replacing oil as a fuel by 2020, both natural gas and coal diminish their share significantly in the 2020s and, much more so, in the 2030s and 2040s. Biomass takes over the lion's share of the fossil fuels until 2035, when hydrogen and electric furnaces start to become economically viable.

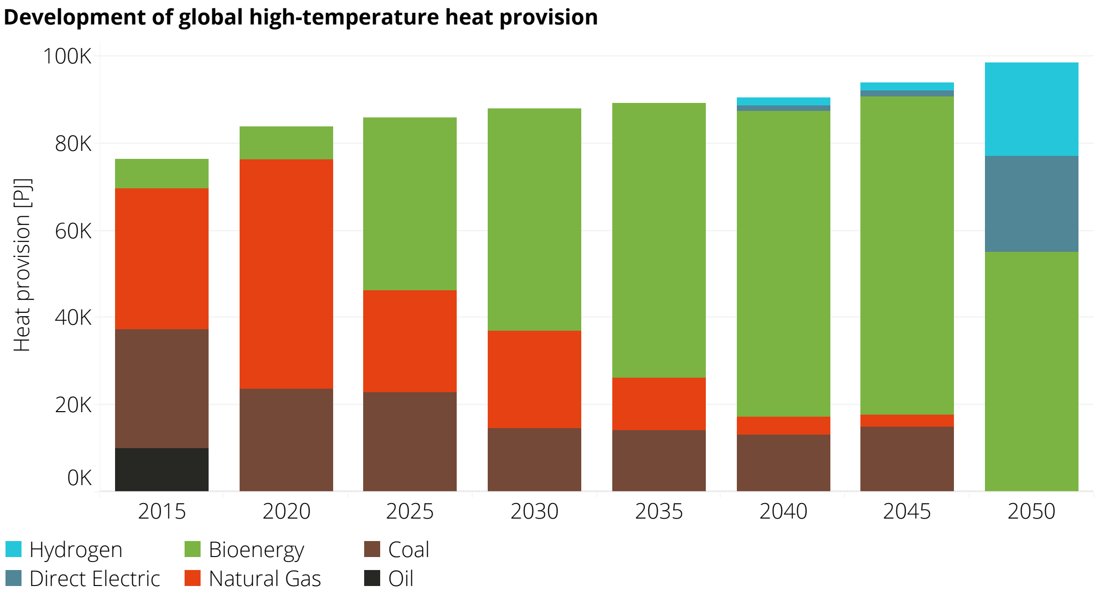

Figure 2.7: Development of global high-temperature heat production.

A similar trend is observed for low-temperature heat generation (see Figure 2.8), with biomass and electric heating meeting most of the heating demands for 2050. Overall, low-temperature heating sees an earlier electrification than its high-temperature counterpart.

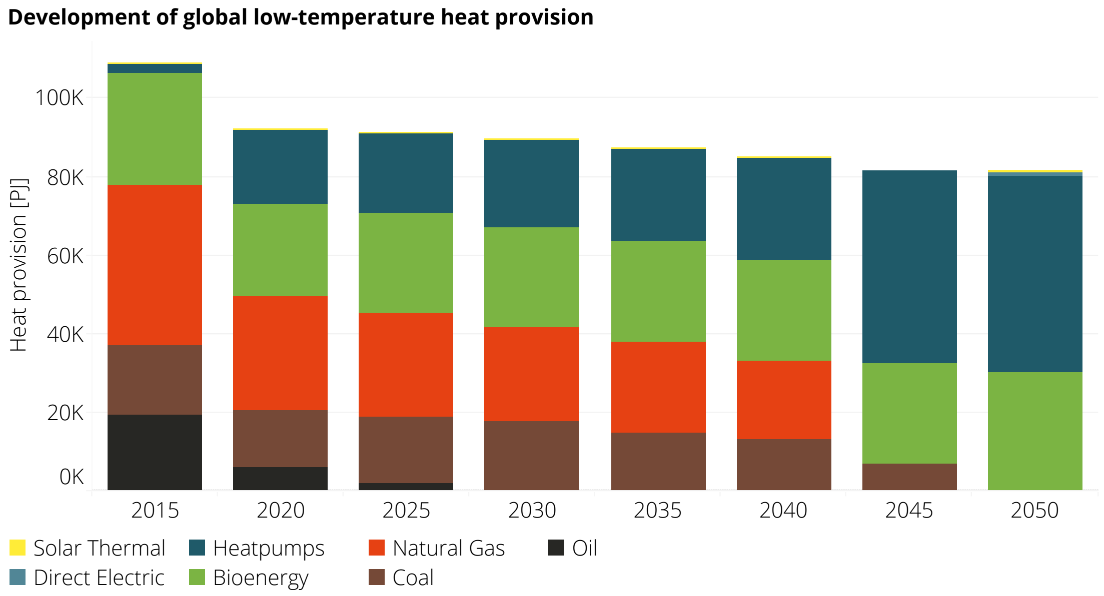

Figure 2.8: Development of global low-temperature heat generation.

Until quite late in the modeling period, fossil fuels remain a major energy source for heating in both high and low-temperature heat generation. Natural gas and coal are the main contributors, both being used as late as 2040 and 2045, before finally being replaced by renewables. This is due to the need for an expanded power system, which has to be constructed beforehand, as well as heat generation from fossil fuels being more efficient than its use for power generation.

### 2.4.2.4 Transportation

Figures 2.9 and 2.10 show the modal share for freight and passenger transportation, respectively. The shift towards renewable fuel sources happens somewhat gradually, depending on the region. On a global scale, freight transportation by road in 2050 is achieved via biofuels and hydrogen, whilst ships utilize biofuels as their energy source. Biofuels are utilized as a transitional fuel source for road-based freight transportation, seeing some early utilization, before hydrogen joins the mix in 2045. The year 2030 poses the year where renewables become increasingly competitive and cost-efficient, which can be observed via a stronger shift away from their fossil counterparts around 2030/2035 across all sectors.

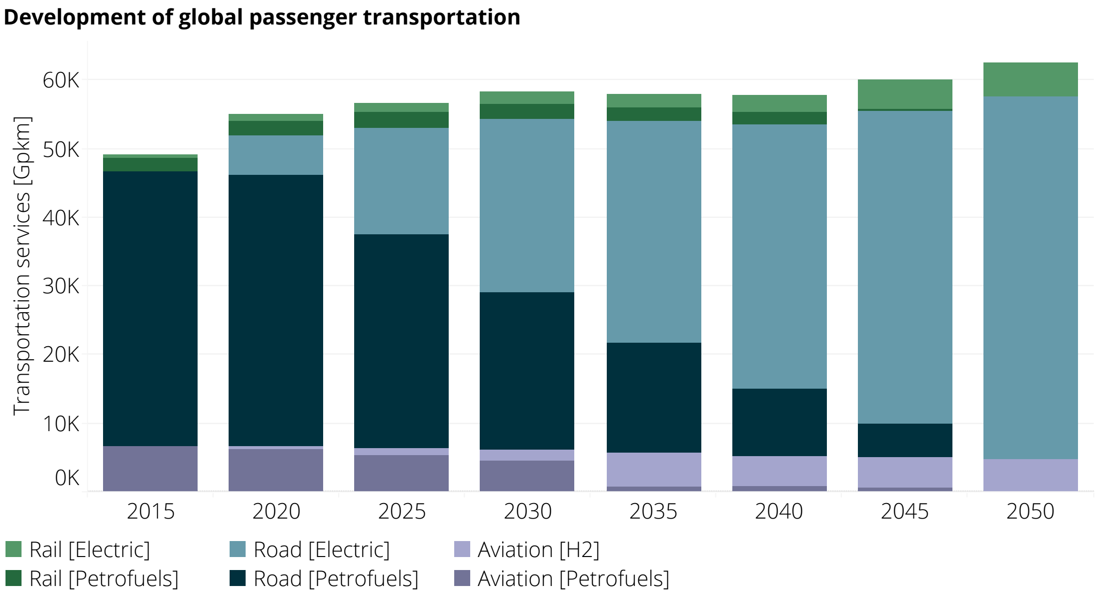

Figure 2.9: Development of freight transportation services.

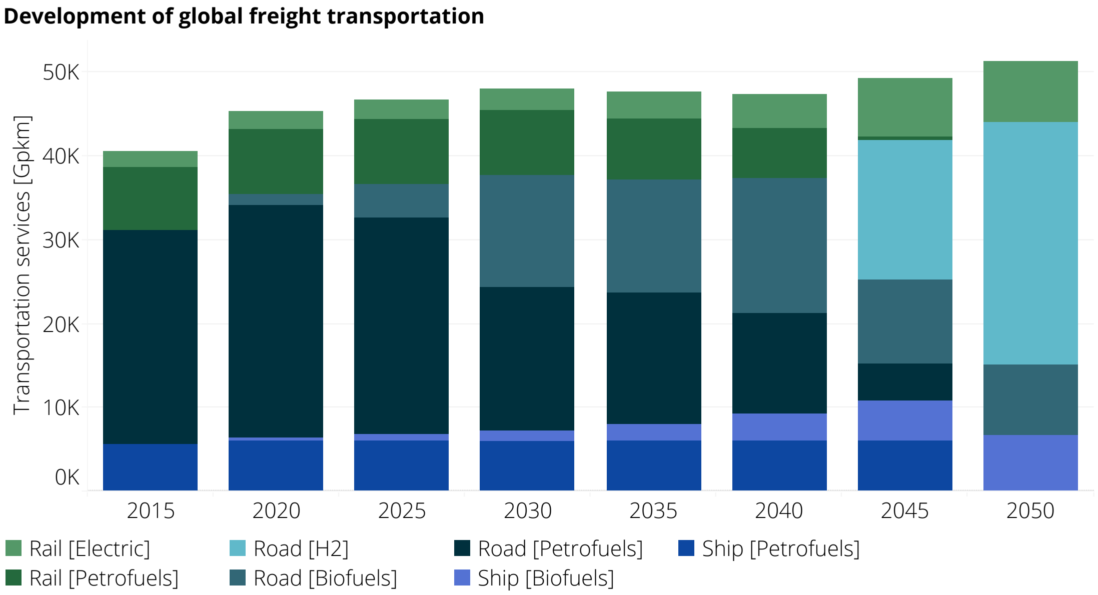

Figure 2.10: Development of passenger transportation services.

### 2.4.2.5 Global $CO_2$ emissions

Figure 2.11 shows the development of global $CO_2$ emissions between 2015 and 2050, distinguished by fossil fuel source (coal, natural gas, oil). Both coal- and oil-based emissions are constantly declining over the years. By contrast, $CO_2$ emissions from natural gas increase between 2015 and 2020, before declining. The period between 2020 and 2025 marks the largest reduction in coal-based emissions, showing a large jump from over 15 Gt to just under 10 Gt $CO_2$ in 2025. Overall, the binding emissions budget, combined with increasing efficiency and reduced cost of renewable technologies, sparks the strong decline of emissions towards 2050.

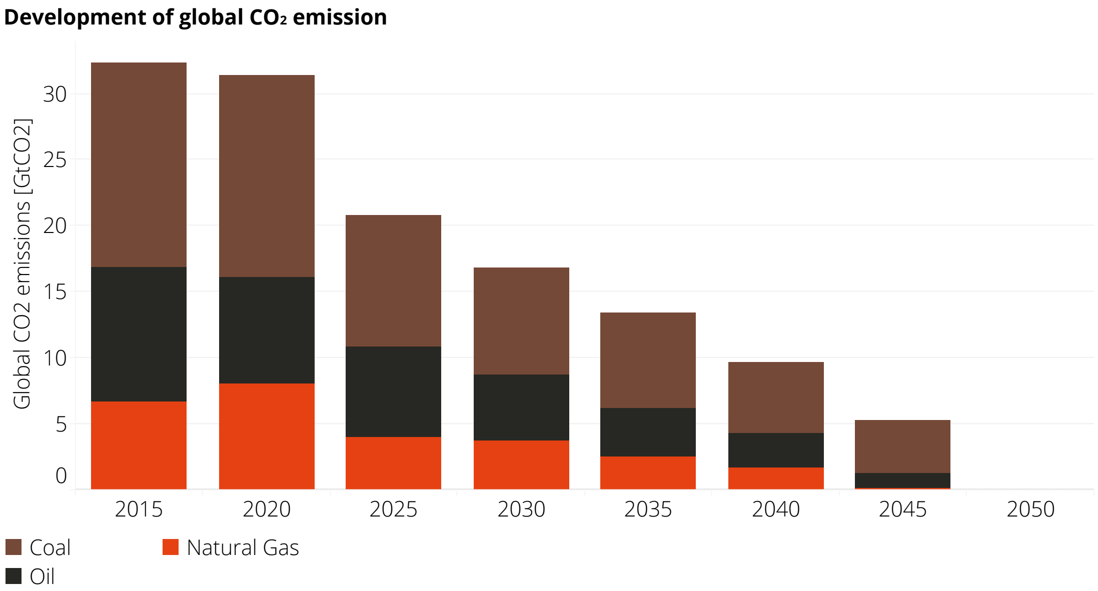

Figure 2.11: Global emissions per fossil energy carrier in billion tons.

### 2.4.2.6 Average costs

Figure 2.12 shows the average costs of electricity generation by the dominating technologies in 2050. The average price per kilowatt-hour for energy supply in 2050 is just above 4 ct/kWh. Solar PV (1.7–3.2 ct/kWh) and hydro (2–2.6 ct/kWh) are the cheapest options for generating electricity, followed by wind onshore (2.9–5 ct/kWh), and wind offshore with 6.4 to 10 ct/kWh. Technologies such as tidal, geothermal, or wave energy plants have been omitted due to their almost nonexistent role in the final energy mix.

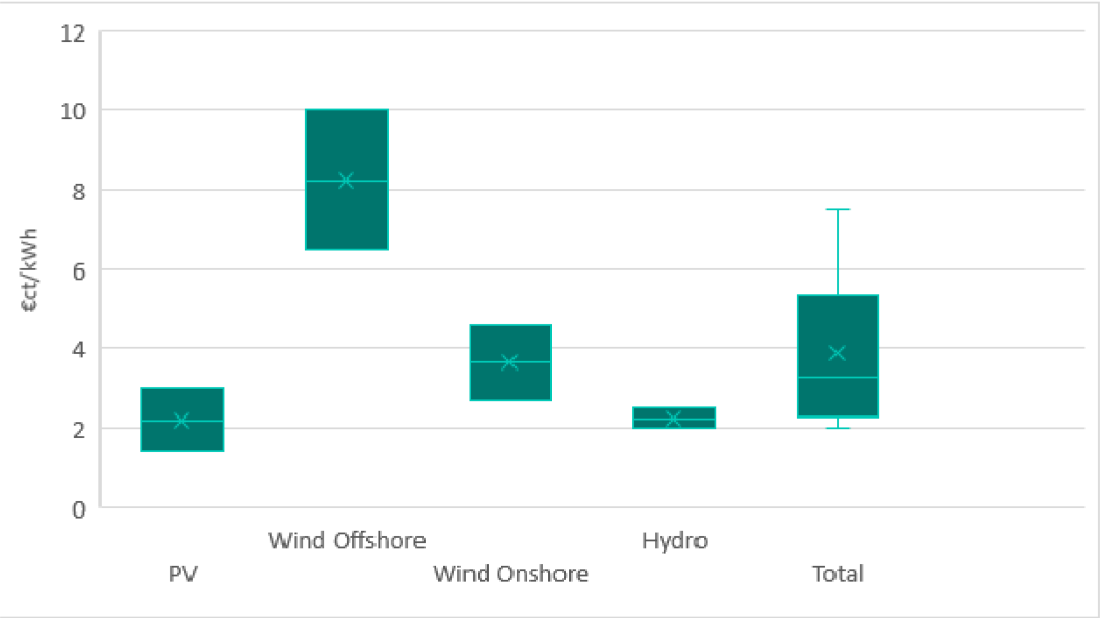

Figure 2.12: Costs of power generation per technology in 2050 in €cent/kWh.

#### 2.4.2.7 Conclusions

Energy system modeling has developed significantly over the last decade, and it is now facing new challenges, as lower-carbon transformation scenarios with higher shares of renewables have to be scrutinized. In this paper, we present a new energy system model, called GENeSYS-MOD, that is specifically designed to calculate global longer-term scenarios for a low-carbon world. GENeSYS-MOD was developed on the basis of the OSeMOSYS, with additional functionalities added (e.g., for storage and transportation). We also provide a translation of the original GNU MathProg version into the GAMS software. GENeSYS-MOD minimizes the total costs for supplying 10 regions of the world with energy (electricity, heat, mobility), such that certain environmental constraints, e.g., $CO_2$ budgets, are respected. The modeling period consists of the years from 2020 to 2050 in 5-year steps, with 2015 as a baseline. Additionally, we split the year into several time periods to simulate different seasons and daytimes and the concomitant fluctuation of renewable energy production. To investigate the interaction between the various sectors, we consider three major types of demand: power, heat, and transport.

After a detailed description of the model, its implementation and the input data, as well as assumptions, the new model is used to calculate low-carbon scenarios for the global energy system, commensurate with reaching the 1.5–2° C target, here defined as a global $CO_2$ budget of 650 Gt for the period 2015–2050. The results of this base period (2015) serve as verification of the functionality of our model as well as a baseline for renewable energy targets. We then allow investments into technologies and the construction of new plants for the calculations of the path towards the year 2050.

The model results suggest a reorientation of the energy system, driven mainly by the climate constraint and decreasing costs of renewable energy sources. As the carbon constraint becomes more binding, less fossil fuels are used to supply energy, and a gradual shift towards renewable sources is observed, accompanied by sector coupling to the benefit of electricity consumption, and some new technological trends, such as the introduction of hydrogen in the transportation sector. The energy mix in 2050 is based on wind and solar power, biomass, and hydropower as the main energy sources. To a smaller degree, geothermal and tidal power plants provide energy as well. Depending on the region, some fossil fuels are phased out as early as 2035 with most fossil fuels being replaced by 2045.

Since the two main sources of renewable energy in our model, wind, and solar power, produce energy in the form of electricity, we observe a strong sector-coupling of the power sector with both the heat and transport sector. In the heating sector, heat pumps, and direct heating with electricity convert power into heat. In the transport sector, electricity is directly used in battery electric vehicles and electric rails as well as converted into hydrogen to provide mobility where the direct use of electricity is not possible. In conclusion, the energy system drastically changes from a dependency on natural gas, crude oil and coal to a system based on wind and solar power as well as biomass within 35 years. This increases overall power consumption over our modeling period, more than tripling the overall production of power compared to 2015.

All models should provide insight, not blunt numbers, and we need to point out shortcomings and future refinements of GENeSYS-MOD as well. At the current, quite aggregate level, we are not considering regional specificities, for example resulting from specific preferences with respect to certain technologies which are not modeled in our normative approach. Also, work needs to continue on the regional and temporal breakdown, in particular given the high share of fluctuating renewables. Issues like hourly storage and more granular time slices have yet to be considered (a case study on the transformation of the energy system in India (with a 10-node-approach) has been done and was published earlier this year (Löffler, Hainsch, Burandt, Oei, and Hirschhausen 2017). Current projects include model applications for India, Europe, and China).

Renewable energy generation has the problem of the potentially high fluctuation which is inherently given for technologies like wind turbines or solar plants. Providing sustainable energy despite depending on external influences like weather is one of the major challenges when considering renewable energies. These issues are not sufficiently represented in our model, since the current implementation only makes use of six time slices and ten regions. Since we operate on a fairly accurate time-basis for things like energy or heat demand, but on a very large scale with our regional setup, data collection can become quite challenging, often leading to the need for assumptions to calculate certain values. Especially with the fluctuating nature of renewable energy sources and the implementation of storage systems, more detailed data is needed.

To be able to better simulate the fluctuating nature of renewables, adding more time slices and day types might increase model accuracy. Especially (short-term) storages and their implementation profit from smaller timeframes with different demand and supply factors. Also, possibly problematic events such as multiple days with very low wind or sun hours might be simulated as a result. Thus, while our current results indicate that a 100% renewable energy system by 2050 can be achieved and show first directions towards its realization, further research can improve upon these findings and present more insights about the exact measures needed to reach an optimal outcome.

#### 2.4.2.8 Assessment of solar PV potentials

The assumed solar PV potential has to be also critically reviewed. The assumed globally available area of 59201 km$^2$ as presented in Section 2.3.8.2.1 for utility-scale PV equals roughly 0.04% of the total global land area. As this area is quite limited, it drives the results regarding the utilization of solar PV. Especially in certain regions, this leads to a comparatively low share of solar PV, as for example, in the Middle Eastern region. In these regions the *optimal* areas for solar PV are exhausted[2], such that the *average* solar PV locations compete with the *optimal* wind locations. On the one hand, sensitivity analyses have shown that changing the capital and fixed costs for solar PV and wind to 2021 cost projections, a globally increased share of solar PV can be observed, as this leads to the *average* solar PV locations provide cheaper electricity than *optimal* wind locations in various of the modeled regions. On the other hand, however, the overall solar PV potential (and thus, also the share of *optimal* locations) is comparatively low, especially considering other studies in this field. For example Bogdanov et al. (2019) assumes that around 6% of the regionally available landmass can be used for the installation of solar PV plants. Additionally, the exclusion of PV sites of irradiation of 4 kWh/m$^2$/d and less proves a further limitation of the assumed

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[2] In GENeSYS-MOD, the areas are divided in *inferior*, *average*, and *optimal* locations.

solar PV potentials. With this limitation, a majority of the sites in Germany, for example, are excluded from the considered solar PV potential, although already today, solar PV power proves to be one of the least-cost options for electricity in Germany.

Overall, with more updated assumptions regarding the potentials and cost-projections of solar PV, a substantially higher share of solar PV in the electricity and final energy mixes are very likely to be seen. In this regard, the average electricity cost are proven to be even lower compared the ones presented in Figure 2.12. This finally also drives the deployment of direct electrification technologies in all non-electricity sectors and a lower share of biomass could very likely to be observed with updated solar PV potentials and costs.

# Chapter 3

# Lessons from modeling 100% renewable scenarios using GENeSYS-MOD

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This chapter is based joint work with Pao-Yu Oei, Karlo Hainsch, Konstantin Löffler, and Claudia Kemfert published in *Economics of Energy & Environmental Policy* 9 (1) under the title: "Lessons from Modeling 100% Renewable Scenarios Using GENeSYS-MOD".

## 3.1 Introduction

### 3.1.1 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 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 Bog-

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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)

danov, 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% renewable energy sources (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% RE 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.

### 3.1.2 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 3.2) with respect to spatial (Section 3.3) and temporal resolution (Section 3.4) as well as sufficient detailed description of the energy system transition effects (Section 3.5) and result interpretation (Section 3.6). The aim of this paper is therefore twofold, to better understand and interpret existing models as well as to improve future modeling exercises.

## 3.2 Methodology

### 3.2.1 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 3.1). 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.

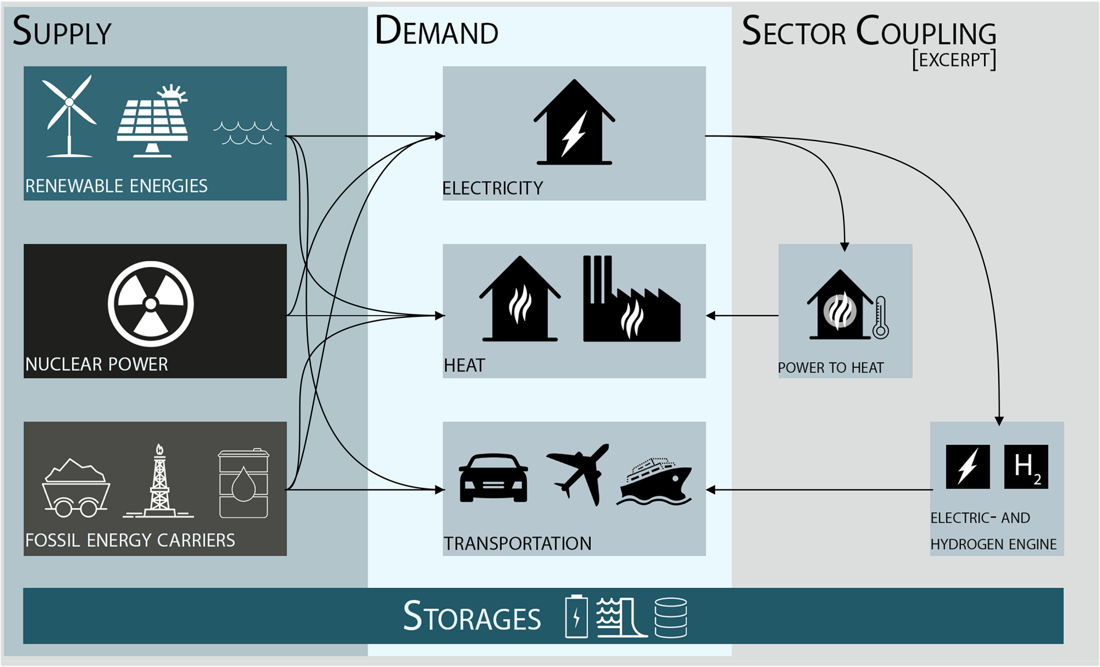

Figure 3.1: Description of GENeSYS-MOD. Source: Own depiction based on Löffler, Hainsch, Burandt, Oei, and Hirschhausen (2017).

### 3.2.2 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. 2021) and Colombia (Hanto et al. 2019).

## 3.3 Choosing the best spatial resolution

### 3.3.1 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 3.2). 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

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

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.

### 3.3.2 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.

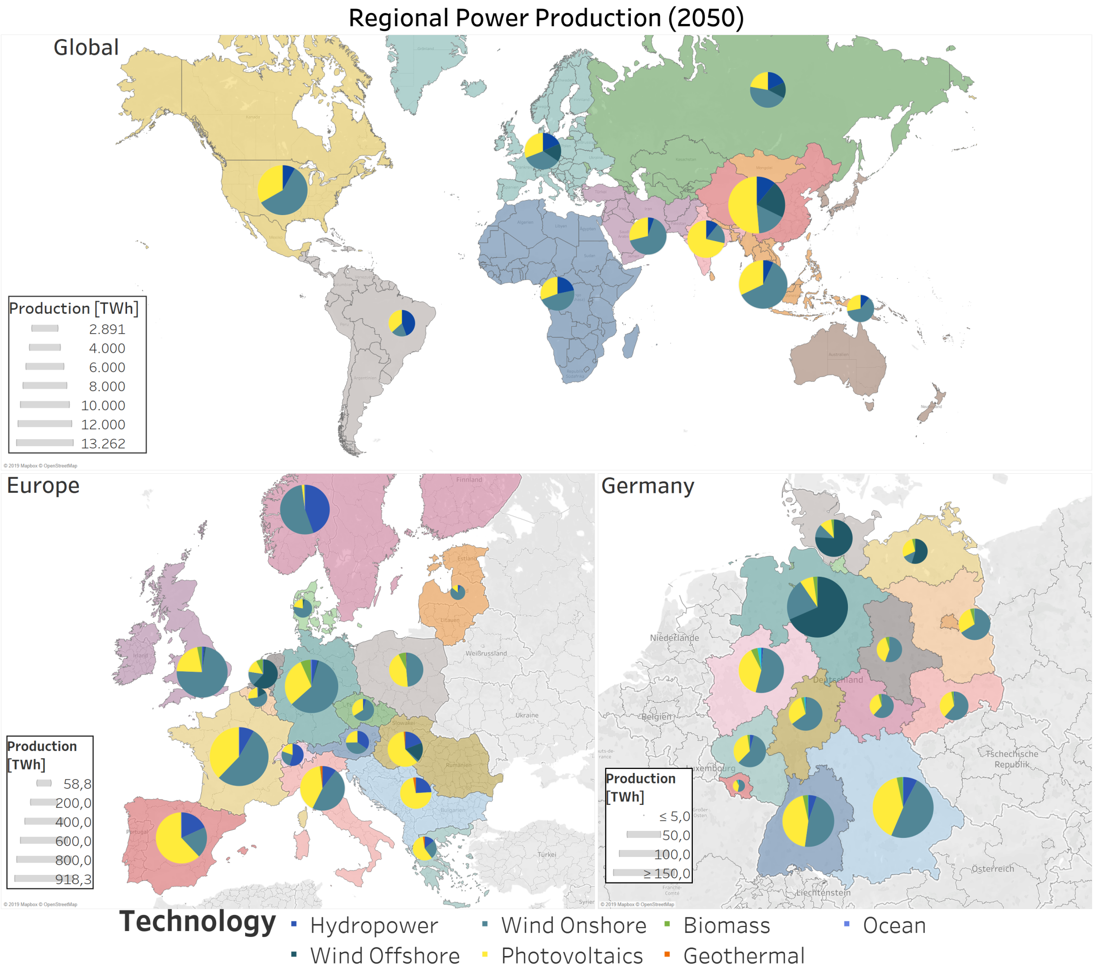

Figure 3.2: Scaling down 100% Renewable scenarios - for the World, Europe and Germany. Source: Own illustration based on Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017), Löffler et al. (2019), and Bartholdsen et al. (2019).

Extreme examples for this were examined by us within South Africa (Hanto et al. 2021) 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 3.3. 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. 2021). 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.

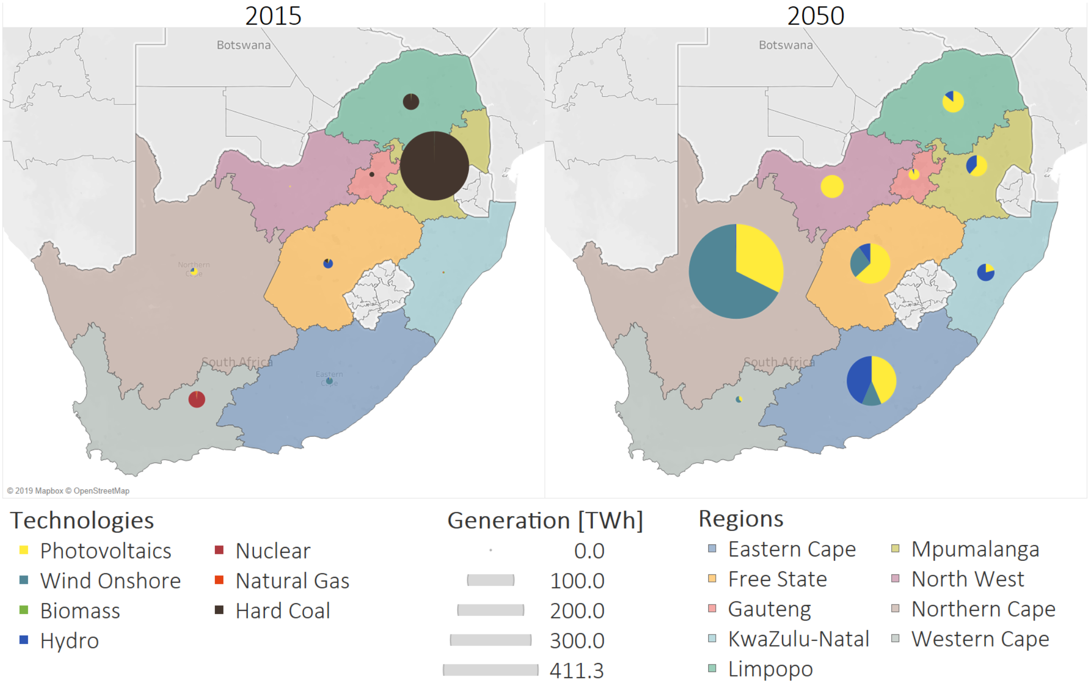

Figure 3.3: Change of regional power production in South Africa. Source: Own illustration.

## 3.4 Temporal aspects of modeling

### 3.4.1 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 73rd hour with ramping constraints was used as a baseline. As shown in this Figure 3.4, the reduction from every 73rd to every 25th 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.

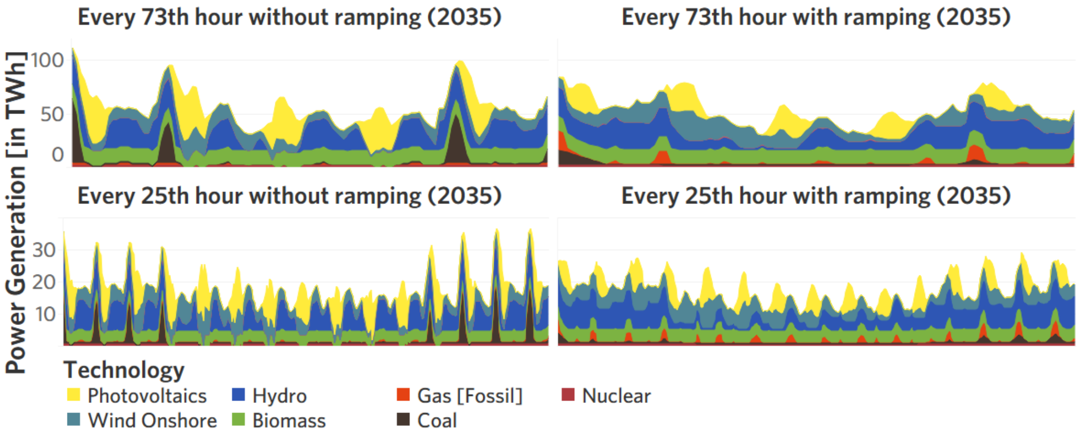

Figure 3.4: Effects of more detailed temporal resolution in comparison to better technical representation of ramping. Source: Adapted from Burandt et al. (2019)

### 3.4.2 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 3.4.1), 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 3.5 shows the differences between the BASE scenario, one including reduced foresight (RED) and one that additionally introduces political boundaries and barriers (POL).

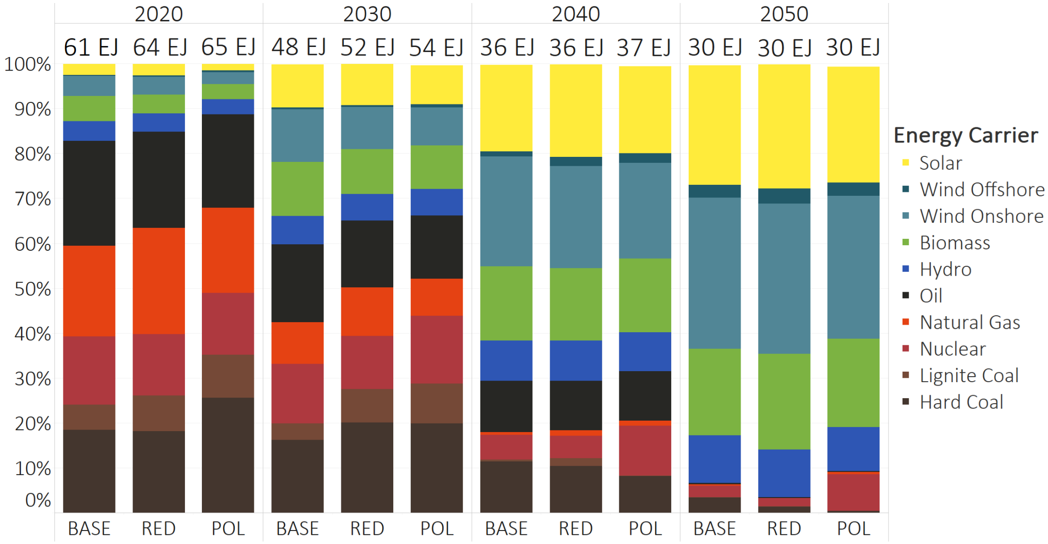

Figure 3.5: Primary energy supply, both relative, as well as total amount in Exajoule (EJ) for Europe. Source: Adapted from (Löffler et al. 2019)

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 3.6) 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.

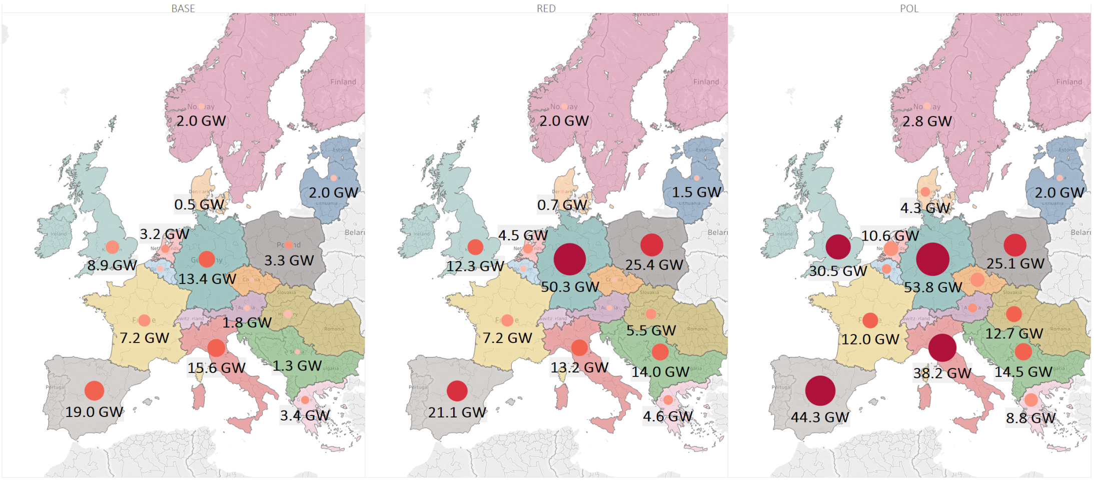

Figure 3.6: Total stranded assets for coal- and gas-fueled power generation in the year 2035 across Europe. Source: Adapted from Löffler et al. (2019).

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.

## 3.5 More detailed analysis of sectoral transitions

### 3.5.1 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 °C, 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 3.7). 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.

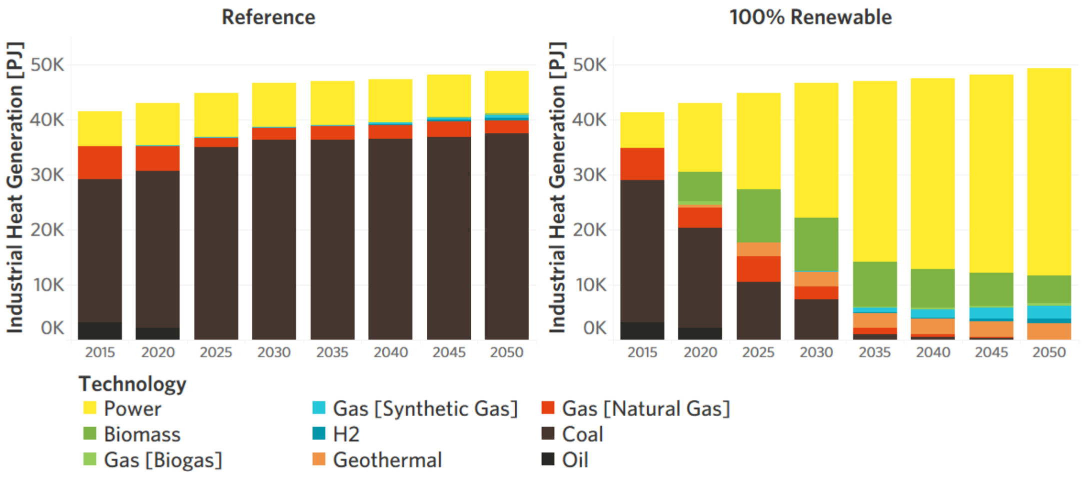

Figure 3.7: Decarbonization of industrial heat in China. Source: Adapted from (Burandt et al. 2019).

### 3.5.2 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 3.8), 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%,

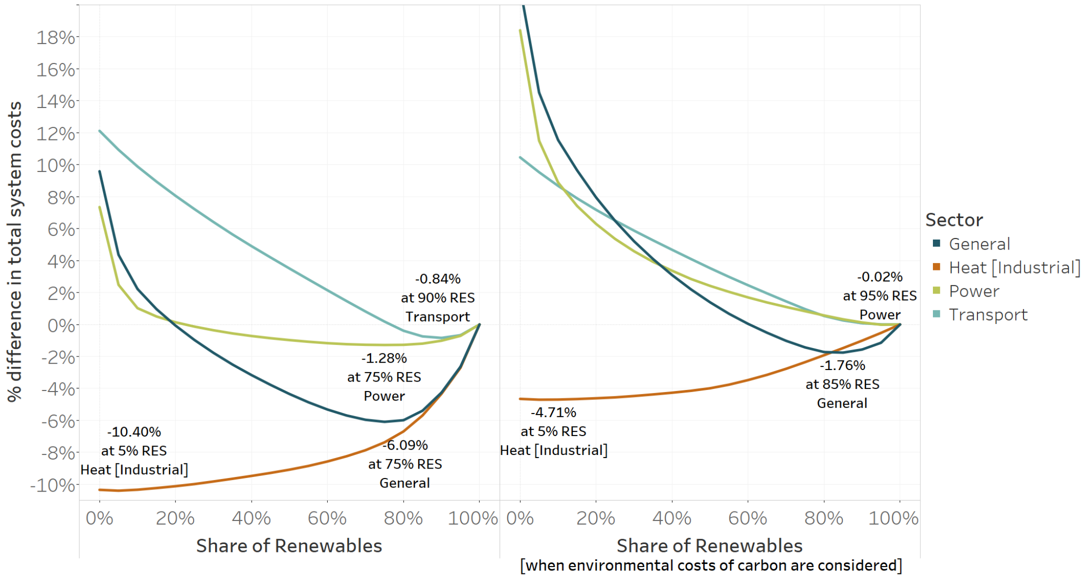

Figure 3.8: Calculating an optimal renewable share for Mexico. Source: Adapted from Sarmiento et al. (2019).

### 3.5.3 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. 2021) 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 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 & 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 3.9).

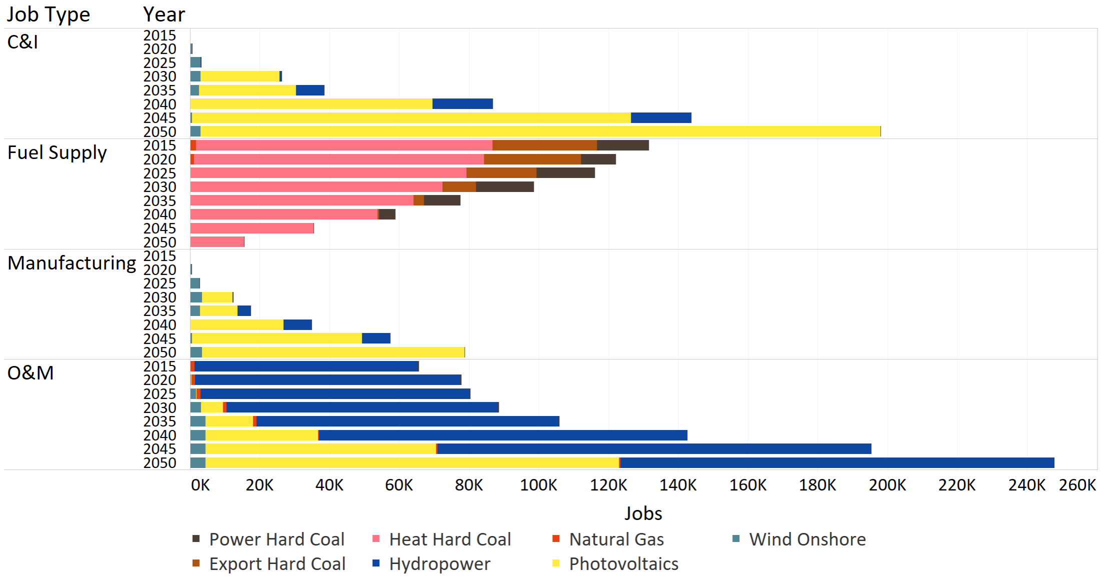

Figure 3.9: Employment effects for 100% renewable scenarios in Colombia. Source: Adapted from Hanto et al. (2021).

## 3.6 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 shortcom-

ings 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 (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 poten-

tial 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., computable general equilibrium (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.

# Part II

# REGIONAL APPLICATIONS

## Chapter 4

# Modeling the low-carbon transition of the European energy system

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This chapter is based joint work with Konstantin Löffler, Karlo Hainsch, 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".

## 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 2017a; 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 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).

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

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 (M. 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 2017a).

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, Echeverri, 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. (2019) 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.

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.

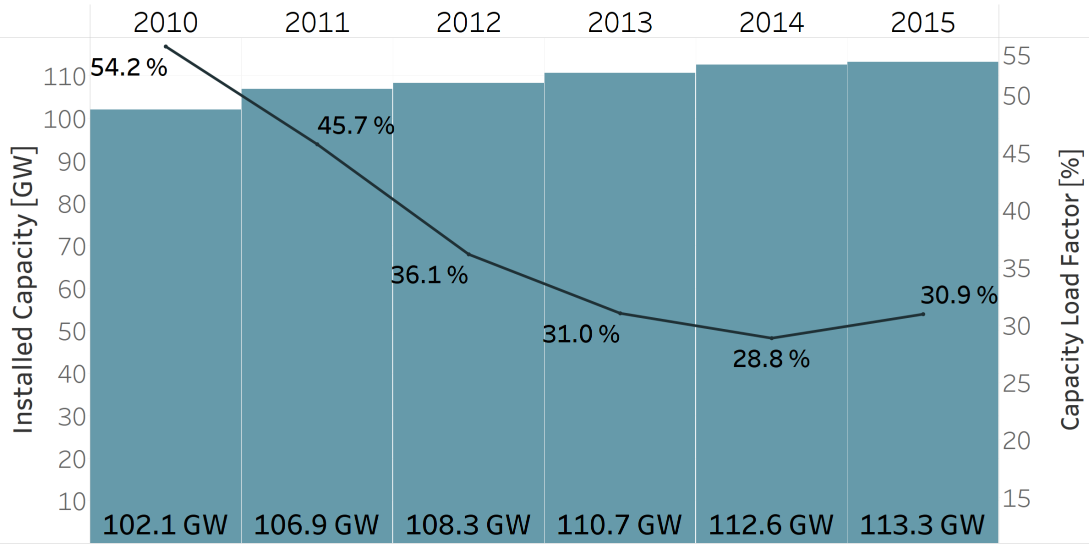

Figure 4.1: Installed natural gas capacities and their yearly load factor for Germany, Italy, UK, and the Netherlands. Source: Own illustration, based on Eurostat (2018) and European Commission (2018a).

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 European Union (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 2018b). Together with the EU's nationally determined contribution (NDC) to the Paris Climate Agreement (UNFCCC 2015), each European member state sets explicit targets for their future energy systems Greenhouse gas (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 renewable energy sources (RES) was mainly made possible 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

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[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 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.

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.

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

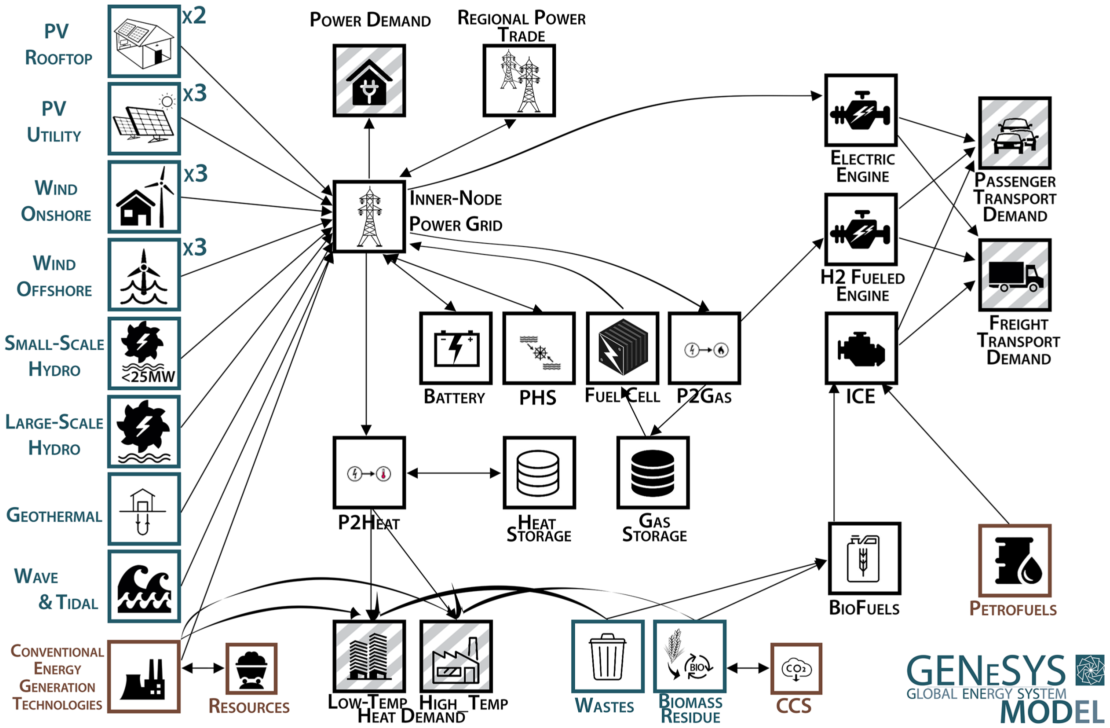

Figure 4.2: Model structure of GENeSYS-MOD v2.0. The model differentiates between two different kinds of rooftop PV (residential, commercial), and three categories of utility PV, onshore, and offshore wind (optimal, average, and inferior for utility PV and onshore wind; shallow, transitional, and deep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

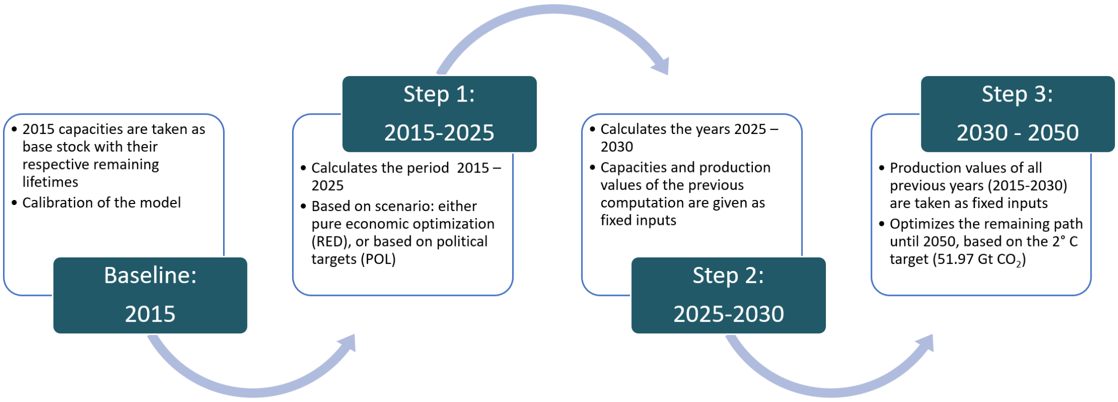

Figure 4.3: Computational process of the reduced foresight scenarios (RED & POL). Source: Own illustration.

## 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.

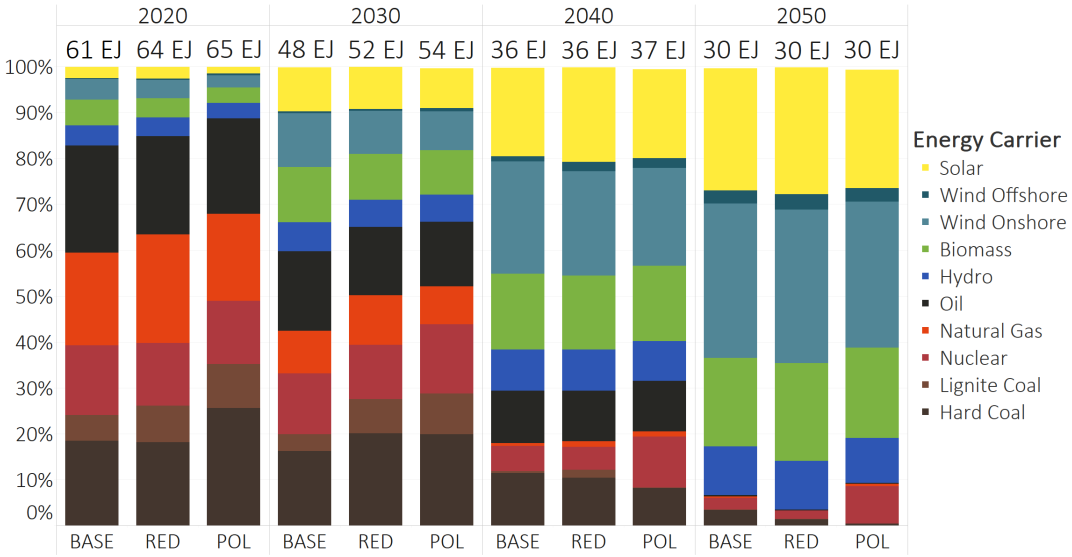

Figure 4.4: Primary energy supply for the years 2020, 2030, 2040, and 2050, both relative, as well as total amount in Exajoule (EJ). Source: Own illustration.

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.

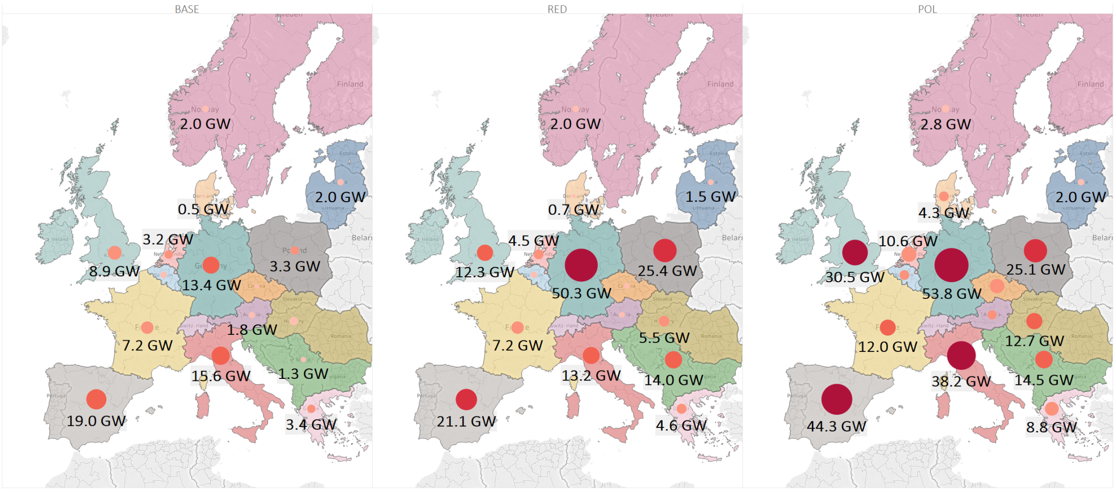

Figure 4.5: Total stranded assets for coal- and gas-fueled power generation per region in the year 2035. Source: Own illustration.

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.

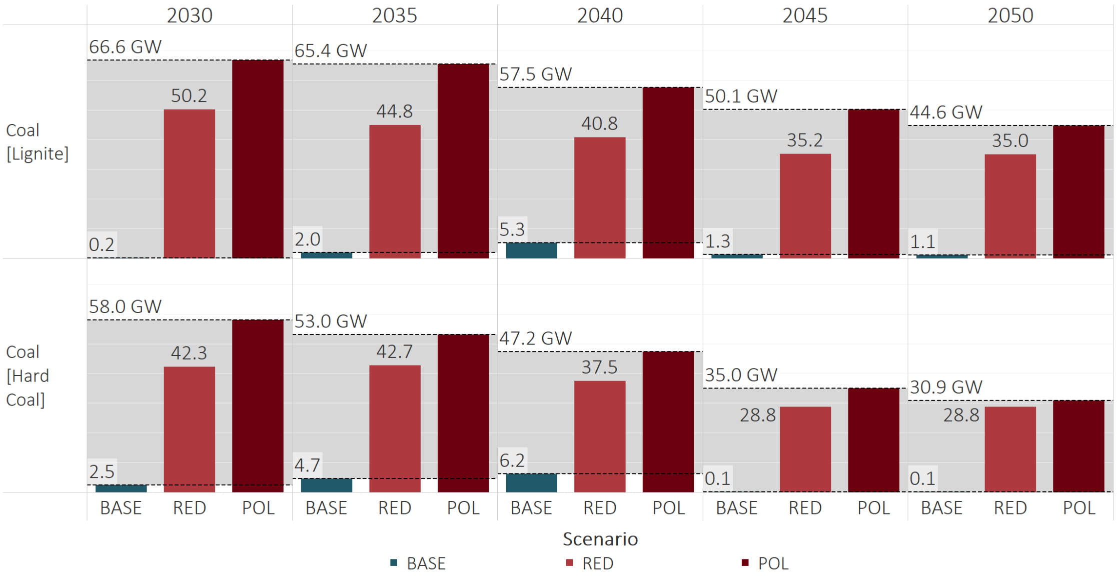

Figure 4.6: Total amount of unused capacities for coal-based power plants. Source: Own illustration.

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.

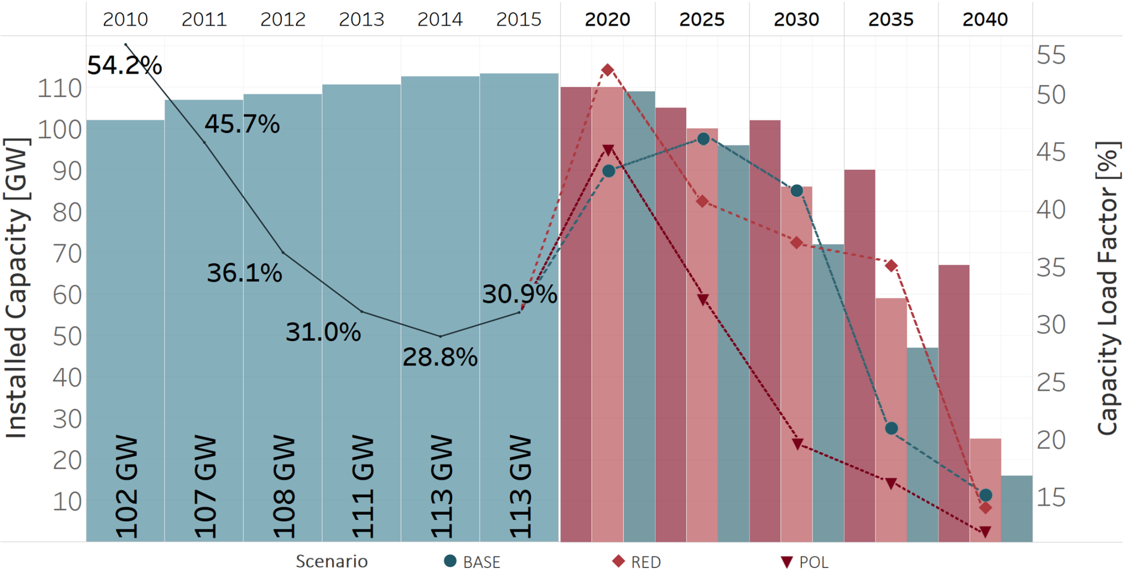

Figure 4.7: Gas power plant capacities and load factor for Germany, Italy, UK, and the Netherlands. Source: Own illustration, data for 2010-2015 based on Eurostat (2018) and European Commission (2018a).

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 biofueled 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]

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[5] Also, methane leakage is not included in the scope of the model when considering CCTS technologies.

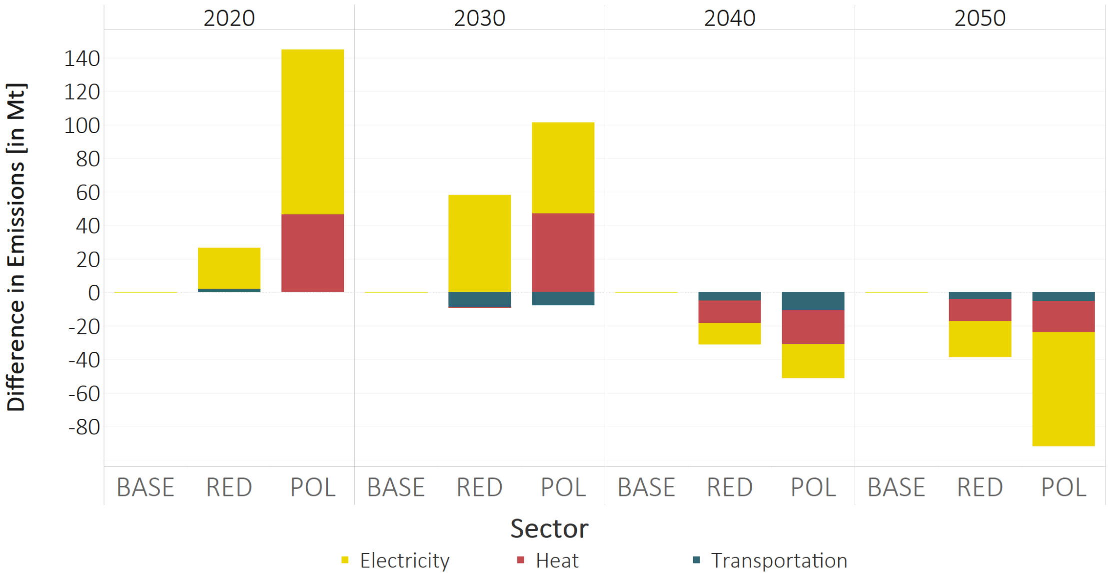

Figure 4.8: Emission differences between scenarios for the sectors electricity, heat, and transportation in Mt $CO_2$ in comparison to the Base scenario. Source: Own illustration.

*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€/t$CO_2$ (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€/t$CO_2$ to the current EU Emissions Trading System (ETS) price (29€/t$CO_2$ 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 ef-

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[6] See https://markets.businessinsider.com/commodities/co2-european-emission-allowances; last accessed 25.04.2021.

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

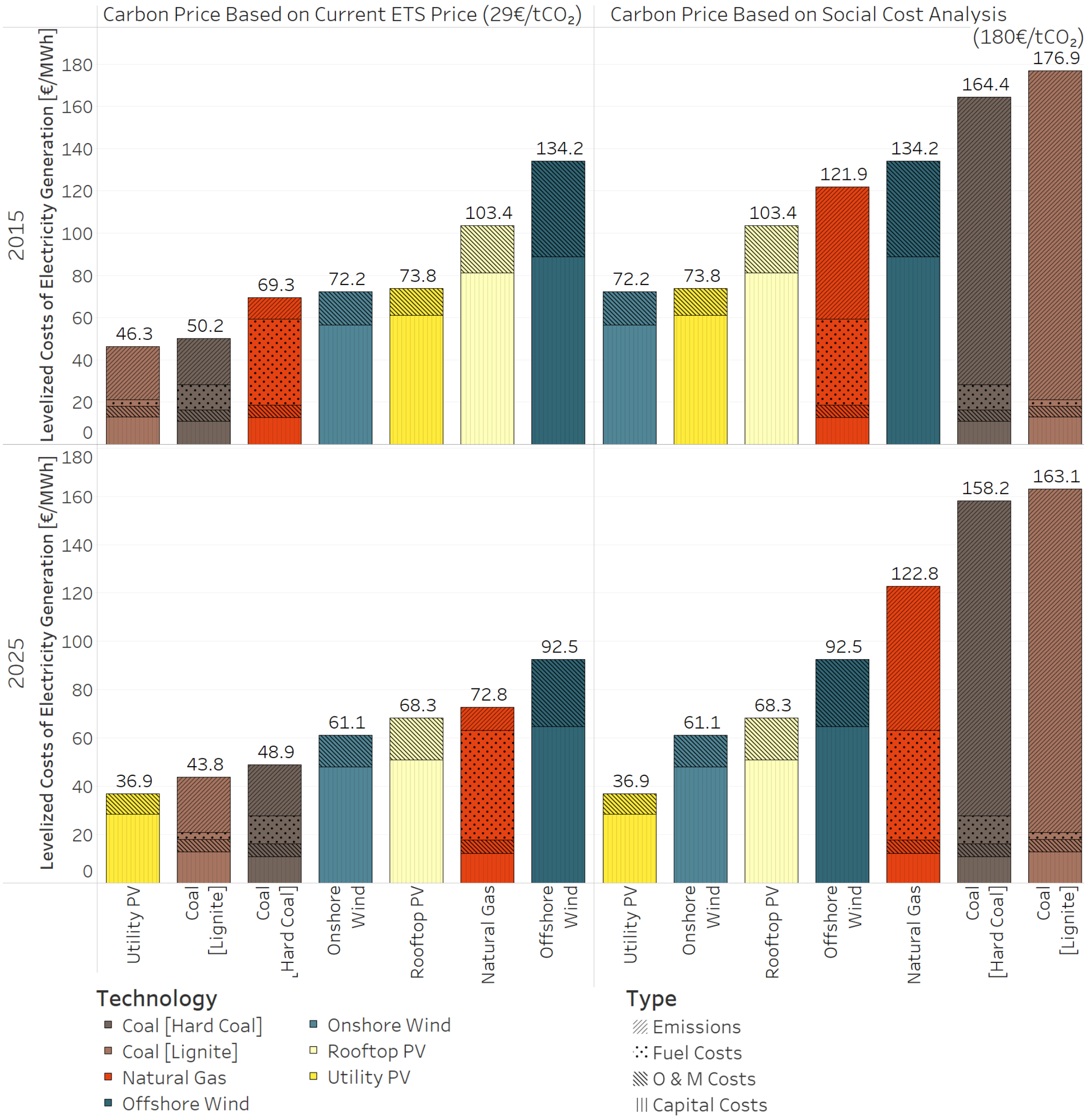

Figure 4.9: Levelized cost analysis for key technologies (Average across the modeled regions). Levelized costs are computed given for two different $CO_2$ prices: left shows the merit order for a $CO_2$ price based on current European Emissions Trading System (ETS) prices, whereas the right-hand side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

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

# Chapter 5

# Decarbonizing China's energy system

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This chapter is based on joint work with Bobby Xiong, Konstantin Löffler, and Pao-Yu Oei published in *Applied Energy* 255 under the title: ”Decarbonizing China's Energy System - Modeling the Transformation of the Electricity, Transportation, Heat, and Industrial Sectors”.

## 5.1 Introduction

China plays a very important role for the global low-carbon energy transformation. It is the second-largest economy, as well as one of the major producers of solar photovoltaics (PV) modules and wind turbines (World Bank and Development Research Center of the State Council 2013; Huang et al. 2016). Furthermore, China has shown substantial growth in energy demand in the past and is likely to continue this trend in the future, i.e., already being the largest emitter of greenhouse gases (GHG) worldwide (see Boden, Marland, and Andres (2013) and European Commission (2016a) and Ahmad et al. (2019)).

Relevant research shows that China is able to reduce emissions in it's power sector and achieve the target of peak coal consumption set by itself (compare N. Zhou et al. (2019) and J. Liu et al. (2019)). The transformation of the Chinese power sector is analyzed in studies by J. Liu et al. (2019), He et al. (2016), Liu, Andresen, and Greiner (2018), and W. Liu et al. (2011). Still the aforementioned studies have their focus on the power system with little to no detail of other sectors. Hence, we propose a multi-sectoral approach for modeling the Chinese energy system with an open-source energy system model. An analysis of different pathways for a decarbonization of the sectors electricity, transportation, heat, and industry is carried out. The paper aims to bridge the gap between the different sectoral analyses and to provide a novel, holistic, view on the decarbonization pathways for the Chinese energy system in light of current climate policies.

The paper is structured as follows: Section 5.2 gives an overview and characterization of the Chinese climate and energy policy in the global context of the Paris Agreement and Sustainable Development Goals (SDGs). The relevant literature, the research question, and the research gap are presented in Section 5.3. Following, Section 5.4 gives an overview of the methodology and a description of the key assumptions and data for modeling the Chinese energy system. Furthermore, the characterization and limitations of the utilized model are presented in this Section. The main results are depicted in Section 5.5. To complement the modeling work, the barriers for a transformation are presented in Section 5.6. The paper concludes with recommendations in Section 5.7 and a conclusion in Section 5.8.

## 5.2 Characterization of the Chinese climate and energy policy

On a global scale, the political urgency of reducing GHG emissions is shown in the Paris Agreement, which aims to limit global warming to well below 2 °. A temperature rise beyond this figure would lead to severe environmental and economic risks, as stated by Stern (2007). The announced withdrawal of the United States of America from the Paris Agreement (Averchenkova et al. 2016) and the unclear development in the European Union (Oberthür and Groen 2017) increase the importance of China's role in international climate policies.

To comply with the Paris Agreement, China has underlined its ambition to set an end to the ever-rising consumption of coal, with an expected peak in 2030 or earlier (Wei 2015). Currently, China's coal consumption stayed comparably stable over the last years and the share of coal on the overall energy mix is slightly decreasing each year (compare National Bureau of Statistics of China (中华人民共和国国家统计局) (2019) and Deha (2019)). Among other goals, China especially targets to decrease its carbon intensity by 60 % in comparison to 2005 and to achieve a total installed capacity of wind and solar power of 200 GW and 100 GW, respectively, by 2020. At the beginning of 2019, China had an installed capacity of 174 GW solar PV and thus already surpassed its initial goal for 2020 by 74 % (National Energy Administration (NEA) China 2018). Also, a recent study by N. Zhou et al. (2019) shows that China's $CO_2$ emissions are able to peak in 2025, as compared to its own NDC (peak $CO_2$ emissions in 2030).

In stark contrast to its promising Nationally Determined Contributions (NDCs), China's energy system is still dominated by coal and other fossil fuels. The majority of its coal is being consumed in the industrial and heating sectors – making a decarbonization more difficult than in most other countries, as shown in Fei (2018). The burning of fossil fuels is the primary cause of air pollution, which not only poses a risk to the environment, but also causes a multitude of health problems. Hence, as stated by Fuso Nerini et al. (2018) and McCollum, Echeverri, et al. (2018), a reduction in coal usage will also decrease local air pollution-related issues in China. Thus, a reduction in coal usage contributes to reaching the Sustainable Development Goals (SDGs) of the United Nations (UN). In line with its NDCs proposed to UN, China has published its 13th Five-Year-Plan (FYP) (CCCP 2015), covering short- to medium-term goals of the country from 2016 to 2020, ranging from socio-economic, over industrial, and infrastructural, to environmental aspects. Naturally, both commitments go hand in hand, as a pledge to keeping the 13th FYP on a national level also means achieving its NDCs proposed to the UN.

On the policy side, China can be divided into six vertically subordinated governmental layers: Central, provincial, city, district, town, and village levels, as shown in Dai (2015). These are involved in the implementation process of commands and guidelines within the FYPs by the national leadership in Beijing. On each level, the distinct authority has its own scope to fulfill these commands. Most policies are primarily within the provincial or city level and include detailed target implementations and resource allocations. Within the 13th FYP, the Chinese government tries to re-centralize the federal energy structure of the previous decades to avoid possible struggles caused by clean energy drafting of weaker ministries (compare Arent et al. (2017)).

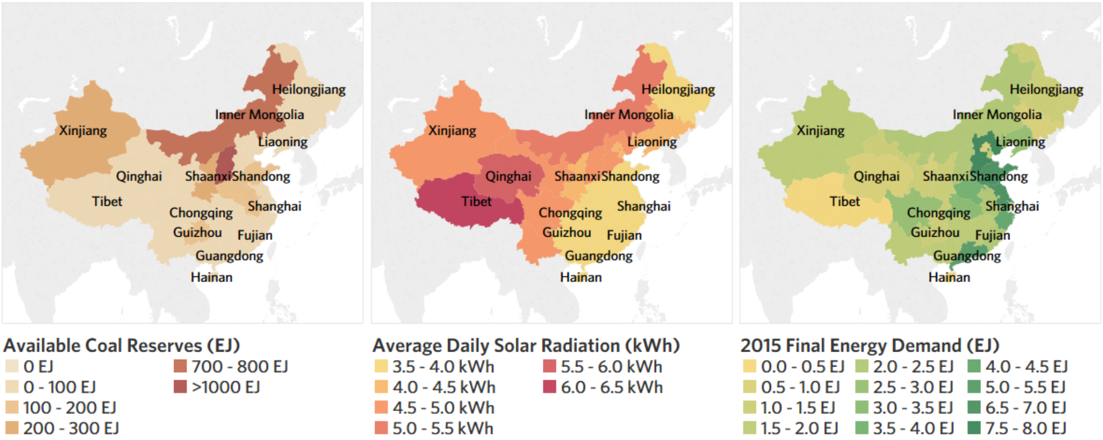

Figure 5.1: Overview of available coal reserves (in EJ) as well as solar radiation (in kWh/d) and final energy demand (in EJ) per Chinese province. There is a regional disparity in the availability of energy sources and demand centers. Although not displayed in this picture, neither wind and hydro-power potentials are available in high energy-consuming provinces. Source: Own illustration.

In the north, the country still features vast coal deposits, mostly found in the Inner Mongolia Autonomous Region and the Shanxi province. China's abundance of renewable energy sources (see Figure 5.1) will allow and accelerate its transformation towards a sustainable energy system (compare W. Liu et al. (2011)). As for variable renewable energy sources (RES), sizable solar PV potentials are mainly aggregated in the central-west and central-south (as analyzed by He and Kammen (2014)), while onshore wind potentials are primarily situated in the Inner Mongolia Autonomous Region (see He and Kammen (2016)). Given the enormous electricity demand in the population-dense coastal-east, large investments into expanding the electricity network are to be expected throughout the decarbonization process of the power sector, as depicted by He et al. (2016) and Breyer et al. (2015).

## 5.3 Status quo of relevant literature

Concerning the decarbonization of energy systems, a large variety of studies is available. However, most studies are focusing on a global energy system with little to no regional detail. Deng, Blok, and Leun (2012) use an Integrated Assessment Model (IAM) to analyze the possibility of transitioning to a global sustainable energy system. They present a feasible pathway for reaching 95% sustainable energy supply in 2050. The importance of technology diffusion of renewable energy sources, such as solar PV or wind, for reaching the climate goals of the Paris Agreement is shown by an analysis by Huang, Chen, and Anandarajah (2017). Further global studies look at 100% renewable energy systems. Only looking at the power sector, Bogdanov et al. (2019) shows the possibility of reaching an energy system based on 100% renewables. Similar findings are concluded by Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) and Tokimatsu et al. (2018). Both also include other sectors apart from the power sector to provide further insights into the transformation of the global energy system. The importance of extending classic power system models by incorporating interlinked sectors is shown by Pursiheimo, Holttinen, and Koljonen (2019). This importance is also reflected by the extensive global study of a 100% renewable energy system provided by Ram et al. (2019). Overall, the feasibility of an electricity system based solely on renewable energies is currently extensively discussed (compare Heard et al. (2017) and Brown et al. (2018)).

Also, various studies exist which focus on different regions of the World in detail. Jacobson et al. (2015) showed that for the United States, a 100% renewable power system, solely based on hydropower, solar PV, and wind power is technically and economically feasible. Similar findings regarding the power system are provided in a study by Connolly, Lund, and Mathiesen (2016) and Child et al. (2019) for Europe. In the context of a 100% renewable European energy system, Steinke, Wolfrum, and Hoffmann (2013) analyze the trade-offs between grid and storages and conclude that investments into both technologies are needed. Kasperowicz, Pinczyński, and Khabdullin (2017) reviewed technical optimization vs. economical optimization in the context of a 100% renewable energy system and argued that large-scale installment of batteries could increase the stability of an energy system. Also regarding Europe, Gerbaulet et al. (2019) show that reduced foresight in energy system models can lead to a substantial amount of stranded assets. The assumption of decreasing or increasing energy efficiency is also highly relevant when looking at different energy systems models. Tvaronavičienė et al. (2018) showed within their analyses that especially for their selected European countries, the energy intensity would not decrease considerably until 2050. They claim that mostly behavioral aspects lead to this aspect. Apart from Europe or the United States, other regional studies are available. For Germany, Müller et al. (2019) present a modeling framework for multi-modal energy systems. In their work, they show that sector-coupling, specifically the electrification of heat and mobility, is needed to reach Germany’s climate targets, a result also highlighted by the recent study of Bartholdsen et al. (2019). Furthermore, a multi-sectoral study with similar findings is available for India (compare Lawrenz et al. (2018)).

Apart from the aforementioned regional studies, some energy system analyses targeting China are available. An assessment of a renewable power system is conducted by W. Liu et al. (2011). They show that China is currently in a phase of rapid technological deployment and that China has an abundant potential of renewable energy sources. Thus, they conclude that a 100% renewable power system is not unreasonable. Breyer et al. (2015) also looked at the transformation of the power system in China. By aggregating China into larger regions and including neighboring countries, they showed that whole North-East-Asian region could be transformed to use 100% renewables in the power sector. Their results furthermore highlight that implementing an area-wide power grid infrastructure reduces the need for excess power generation capacities and thus further decreases the total system costs. He et al. (2016) present a systems approach for a decarbonization of the Chinese power system. They show that for China, substantial reductions in GHG emissions from 2030 on are needed in order to stay below 2 °. Also, large extensions in the power grid infrastructure are required to reach an 80% carbon reduction in 2050.

More recently, Liu, Andresen, and Greiner (2018) presented a cost-optimal design of a simplified, highly renewable Chinese electricity network. They show similar findings regarding the needed grid expansion, compared to He et al. (2016). Most importantly, long-range power transmission is required, given China's regional disparity of renewable resource availability and demand centers. Endogenously incorporating the electricity requirements from other sectors (industry, building, transport, and agriculture) to an energy system, J. Liu et al. (2019) showed that the future development of coal power plants is a crucial factor in determining the time of the emissions peak and thus for reaching China's NDCs. Zhang, Ma, and Guo (2018) aggregated China into seven regions and analyzed the development of the Chinese power system until 2050. They also showed that China's $CO_2$ emissions are able to peak in 2030. Looking at the requirements for China's renewable energy transition, Wang et al. (2019) showed critical minerals and rare earths may be limiting the deployment of both wind and solar PV. They argue that the transformation of China's power system has to be more in line with China's critical mineral endowment. Also, several studies, specifically analyzing the requirements, impacts, or complementarity of solar PV and wind are available. Tu, Betz, Mo, and Fan (2019) state that the profitability of onshore wind and solar PV is highly depended on the feed-in-tariff. With the current prospect of a diminishing feed-in-tariff, the profitability of solar PV and onshore wind will decrease. Also, Tu, Betz, Mo, Fan, and Liu (2019) identified carbon pricing as a primary factor for reaching grid parity in China. The importance of coordinated operation or combined wind-PV-thermal dispatch is presented in different studies by H. Zhang et al. (2019), Tan et al. (2019), Sun and Harrison (2019), and Ren et al. (2019). Summarizing, the current literature regarding the Chinese power sector acknowledges the role of solar PV as driving forces for decarbonization of the Chinese energy system, although S. Zhou et al. (2018) argues that the intermittency of these variable renewables likely increases the electricity costs.

Overall, most studies conclude that significant investments into low-carbon energy technologies are needed to fulfill the Paris Agreement, and even more to reach a maximum global warming of 1.5 ° as shown by McCollum, Zhou, et al. (2018). Also, many studies targeting a limitation of global warming to 2 ° and below rely on a substantial use of carbon capture transport and storage (CCTS)[1] (Huang, Chen, and Anandarajah 2017). Contrary, other articles conclude that there is still a possibility of staying well below 2 ° without an abundant deployment of CCTS (Grubler et al. 2018). This is especially important, as large-scale deployment of CCTS and investment into $CO_2$ infrastructure is rather unlikely (Oei and Mendelevitch 2016). Overall, the role of CCTS and other negative-emission technologies for the future energy system transformation is very uncertain (see Minx et al. (2018)).

Regarding China, He et al. (2017) review the four key drivers that dominate China's energy transformation: resource potential, technology advancement, air pollution control and policy, as well as reform of the power sector. They conclude that China's energy demand can largely be powered by RES, given its vast resource potential in solar and wind (compare He and Kammen (2014) and He and Kammen (2016)). The government, on the other hand, is still heavily invested in both traditional and more advanced, less pollutant technologies. In general, especially solar PV has seen substantially decreasing prices in the last years, which was mainly enabled by the comparative advantage and low market entry barriers in China, as stated by Zhu, Xu, and Pan (2019).

While, in general, 36.2 % of China's total $CO_2$ emissions can be allocated to the operation of coal-fired power plants in the power and heating sectors, the emissions per downstream sector (manufacturing, construction, etc.) are often unclear. A recent survey of Bai et al. (2018) looks at the $CO_2$ emissions embodied throughout the industrial supply chain in China. By mapping inter-industrial $CO_2$ flows across 30 Chinese industrial sectors, the study finds that around 29.8 % of all $CO_2$ emissions of 2012 are resulting from rapid urbanization in recent years. Instead of capping $CO_2$ emissions in upstream sectors (energy generation, exploitation of resources), they propose that a cost-effective and significant reduction in $CO_2$ emissions can be achieved through adopting stronger incentives for more efficient and sustainable material manufacturing and energy use in downstream industries.

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[1] Also named as carbon capture and storage (CCS) in the literature.

A recent joint report by Agora Energiewende and the China National Renewable Energy Center confirms the widely established consensus that China can achieve a 50 % share in renewable energy integration by 2030. In addition to expanding existing wind and solar power capacities by 35 GW and 65 GW respectively, fundamental challenges in China's present energy mix have to be addressed, i.e., over-capacities in coal-fired assets and the lack of accessibility for (new) market participants (Agora Energiewende and CNREC 2018). Furthermore, the continued construction of coal-fired power plants by the Chinese government leads to high risks of stranded assets in the power sector (Fei 2018).

Overall, previous studies have shown that in order to reach the agreed-upon goal of a maximum mean temperature increase of 2 °, extensive expansions of renewable generation capacities are required, and that large-scale installment of nuclear power may not be an economically feasible alternative, as depicted in the works of Huang, Chen, and Anandarajah (2017), Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017), He et al. (2016), Bogdanov et al. (2019), or Breyer et al. (2015).

However, most of the previously mentioned studies, including all Chinese ones, target only the power sector, omitting crucial effects due to sector-coupling (compare He et al. (2016), Huang, Chen, and Anandarajah (2017), Liu, Andresen, and Greiner (2018) or Bogdanov et al. (2019)). Despite the efforts of J. Liu et al. (2019) to expand their power system model by introducing the electricity requirements of other sectors, a full view of other sectors and their corresponding sector-coupling potentials are omitted in this study. Also, although Ram et al. (2019) published an extensive study of analyzing 100% renewables on all sectors, only one distinct scenario has been analyzed, and China has only be looked at in aggregated larger regions. The same is observed in the paper by Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017). It shows the importance of including sector-coupling to an energy system model and also elaborates the possibility of 100% renewables across all sectors. Still, they have a less detailed heating sector (compare Section 5.4), transportation sector (see Burandt, Löffler, and Hainsch (2018)) and a rather rough time-aggregation while modeling only large, aggregated regions.

As of now, a comprehensive analysis of the roles of the different sectors, including electricity, industry, buildings, as well as transport, on a technological level, with possible electrification potentials for China on a detailed regional level of aggregation is missing in the literature. We, therefore, propose a multi-sectoral, bottom-up, techno-economic approach with an accurate regional aggregation for China at provincial resolution. The research tries to provide insights for the following research question: *How does the Chinese energy system in general, and specific sectors in particular, transform by applying different $CO_2$ budgets*?

## 5.4 Methodology

Overall, energy system models can be broadly divided into techno-economic (bottom-up) and macroeconomic (top-down) models, compare Herbst et al. (2012). Techno-economic models permit separating the energy system into different technologies, processes, and interdependencies across energy carriers. This ability to divide the energy system into smaller technology blocks allows the model to internalize the impact of specific policies in each subdivision and to optimize the relationships between sectors, technologies, and regions. On the opposite, techno-economic models neglect severe market imperfections and obstacles in many final energy sectors. Macroeconomic models, on the other hand, sacrifice detailed technical information for a better macroeconomic representation. They try to depict the whole national or regional economies while looking at aggregated effects of climate, energy, or societal change, while attempting to capture links between the energy sector, the economy, and society. The separation between techno-economic and macroeconomic models resulted in the need to develop a new set of models that internalize the advantage of both approaches. Compared to those two categories, Dagoumas and Koltsaklis (2019) review models for integrating renewable energy in the generation expansion planning in three types: *Optimization Models*, *General/Partial Equilibrium* Models, and *Alternative Models*. According to Dagoumas and Koltsaklis (2019), Optimization models are considered as robust models, as they incorporate in detail the techno-economic characteristics of the power system. These models are able to analyze regional and national policies due to their level of detail (regarding technologies, regional aggregation, or temporal resolution).

An important example of techno-economic optimization models is the MARKAL model, developed by the International Energy Agency (Fishbone and Abilock 1981). While MARKAL belongs to the group of optimization models, recent modules try to bridge the gap between the techno-economic and macroeconomic models (Seebregts, Goldstein, and Smekens 2002), one of them being TIMES (The Integrated MARKAL-EFOM System). TIMES combines a technical engineering with an economic approach, thus merging the characteristics of both (ETSAP 2005).

To analyze the effect of different $CO_2$ budgets on the development of the Chinese energy system, we use an enhanced version of the Global Energy System Model (GENeSYS-MOD) (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017). GENeSYS-MOD is a linear cost-optimizing model based on the Open Source Energy Modelling System (OSeMOSYS) (Howells et al. 2011; Gardumi et al. 2018), offering endogenous optimization of different demand sectors assuming an omniscient central planner. Overall, GENeSYS-MOD is similar to the TIMES model regarding its modular structure and general modeling paradigm. The key advantage of GENeSYS-MOD is the open-source approach of code and data. The capacity of GENeSYS-MOD to subdivide the energy system into sectors, technologies, and regions; its ability to account for sector coupling; and its high degree of technological features are necessary characteristics of a model attempting to understand the consequences of exogenous variations in energy and climate policies on each supply option, energy sector, and modeled region.

In this article, we look at the sectors *Power*, *Buildings*, *Industry*, and *Transport* on a provincial level with a reduced hourly time-series. The results of this quantitative method were verified by a combination of expert elicitation and literature research.

Compared to the version of the model presented in Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) and Burandt, Löffler, and Hainsch (2018), several new additions have been made. Firstly, to better represent the need for flexibility options, ramping, together with ramping costs, has been added to the model. Equation 5.1 defines the upward and downward production change ($g^{\Delta+}_{y,l,t,f,r}$ and $g^{\Delta-}_{y,l,t,f,r}$) as difference in the generation per technology ($g_{y,l,t,f,r} * YS_{y,l}$) between the current and the previous time-step $l$. This equation is set up or all years $y \in Y$, time-steps $l \in L$, technologies $t \in T$, fuels $f \in F$, and regions $r \in R$.

$$g_{y,l,t,f,r} * YS_{y,l} - g_{y,l-1,t,f,r} * YS_{y,l-1} = g^{\Delta+}_{y,l,t,f,r} - g^{\Delta-}_{y,l,t,f,r} \quad \forall_{y,l,t,f,r} \tag{5.1}$$

The up- and downward change in production is limited by the yearly capacity $tcap_{y,t,r}$ denoted by the availability factor $AF_{y,t,r}$ of each technology *t* in each year *y* and time-step *l*. To convert the capacity to an limit for the amount of energy, the previous term is multiplied by factor that determines the maximal energy that could be produced by one unit of capacity in one year ($CTA_t$).Furthermore, the up- and downward change is limited by exogenous defined ramping factors $RF^{+}_{r,t,y}$ and $RF^{-}_{r,t,y}$. These factors define how much of the built capacity can be activated or deactivated in each time-step, see Equations 5.2 for the upward ramping limit and 5.3 for the respective downward ramping limit.

$$g^{\Delta+}_{y,l,t,f,r} \leq tcap_{y,t,r} * AF_{y,t,r} * CTA_t * RF^{+}_{r,t,y} * YS_{y,l} \quad \forall_{y,l,t,f,r} \tag{5.2}$$

$$g^{\Delta-}_{y,l,t,f,r} \leq tcap_{y,t,r} * AF_{y,t,r} * CTA_t * RF^{-}_{r,t,y} * YS_{y,l} \quad \forall_{y,l,t,f,r} \tag{5.3}$$

Furthermore, Equation 5.4 adds costs for each unit of energy that has been changed between timeslices (ramped up or down) by applying a cost factor $RCF_{r,t,y}$ on the energy changed. Coal power plants have comparably high and natural gas relatively low costs, and thus, coal power plants will be encouraged to serve as base-load power plants. Contrary, natural gas is used for handling variability and intermittency of RES, together with storage technologies. The annual ramping costs $rc_{y,t,f,r}$ are discounted to the base year ($rc^{D}_{y,t,f,r}$) and included in the objective of the model as depicted in Equation 5.5.

$$rc_{y,t,f,r} = \sum_{l} (g^{\Delta +}_{y,l,t,f,r} + g^{\Delta -}_{y,l,t,f,r}) * RCF_{r,t,y} \quad \forall_{y,t,f,r} \tag{5.4}$$

$$rc^{D}_{y,t,f,r} = \frac{rc_{y,t,f,r}}{(1+DR)^{y-y^{first}+0.5}} \quad \forall_{y,t,f,r} \tag{5.5}$$

The annual discounted ramping costs are added to the total discounted technology costs $ttc_{y,t,f,r}$, together with discounted variable and fixed operating costs $oc^{D}_{y,t,r}$, discounted capital expenditures $ci^{D}_{y,t,r}$, and discounted emission costs $ep^{D}_{y,t,r}$ (compare Equation 5.6). Finally, as seen in Equations 5.7 and 5.8, the sum of all technology costs and storage costs $tsc^{D}_{y,s,r}$ are added to the objective function. This displays the modular structure of GENeSYS-MOD. Although several equations and parameters are added to the original model, only one equation has to be changed to incorporate this new functionality to the model. In general, all key parts of OSeMOSYS and GENeSYS-MOD are formulated in distinct blocks. For an overview of the major blocks of functionality of GENeSYS-MOD, please refer to Appendix D.2.

$$ttc^{D}_{y,t,r} = oc^{D}_{y,t,r} + ci^{D}_{y,t,r} + ep^{D}_{y,t,r} + sv^{D}_{y,t,r} + rc^{D}_{y,t,r} \quad \forall_{y,t,r} \tag{5.6}$$

$$tc^{D}_{y,r} = \sum_{t} ttc^{D}_{y,t,r} + \sum_{s} tsc^{D}_{y,s,r} \quad \forall_{y,r} \tag{5.7}$$

$$\text{minimize} \quad \sum_{y,r} tc^{D}_{y,r} + \sum_{y,r} atc^{D}_{y,r} + \sum_{y,f,r,rr} ncc^{D}_{y,f,r,rr} + \sum_{y,f,r} acc^{D}_{y,f,r} \tag{5.8}$$

The remainder of the model formulation is well presented in other articles. Hence, for further information of the model and the model formulation, please refer to Howells et al. (2011), Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017), and Burandt, Löffler, and Hainsch (2018). A list of used symbols in this mathematical formulation can be found in Appendix D.2. Also, a mathematical formulation in line with the OSeMOSYS- or GENeSYS-MOD-style of defining equations is presented in D.2.0.1.

Furthermore, as the introduction of ramping needs a more detailed time resolution, the approach using representative time-slices was changed in favor of (reduced) hourly time-series as used by the *Dynamic Investment and Dispatch Model for the Future European Electricity Market* (dynELMOD), presented by Gerbaulet and Lorenz (2017a) and Gerbaulet et al. (2019). This time-series reduction algorithm works in three steps. First, every *nth* hour of a full hourly time-series is chosen, starting at a given starting-hour. Additionally, the 12 or 24, depending on target resolution, consecutive hours with the lowest renewable infeed are added. This reduced time-series is smoothed with a moving-average function in the next step to decrease the artifacts and jumps of the new time-series. The window width is defined by hand for each technology. The third step scales the new time-series with a discontinuous non-linear program. For a detailed description of this process, please refer to Gerbaulet and Lorenz (2017a) and Gerbaulet et al. (2019).

Due to memory and computation time constraints, a time-series based on each 73$^{\text{rd}}$ hour was chosen, resulting in 120 time periods. Hence, five consecutive days with a hourly resolution and yearly characteristics have been calculated.[2]

Additionally, to better accommodate the importance of the industry in China, the preexisting structure of high-temperature and low-temperature heat as depicted in Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) has been altered. The new structure features four different temperature ranges with a more distinct differentiation in industrial (0-100°C, 100-1000°C, and >1000°C) and residential heating (0-100°C). For this new representation, a large variety of new technologies has been implemented to allow for alternative options to decarbonize industrial processes of more than 1000°C, as electrification poses only limited options for these cases. This new structure allows for a better illustration of sectoral $CO_2$ emissions, and thus allows for a more detailed analysis of the importance of the industry for a decarbonization of an energy system. This representation is of high importance, as the energy-intensive high-temperature industry (e.g., steel-making, aluminum production) has a large influence and importance for China (National Bureau of Statistics of China (中华人民共和国国家统计局) 2019).

### 5.4.1 Key assumptions and data

For this analysis, nearly all first-level administrative divisions, such as provinces, municipalities, autonomous regions, and special administrative regions are included. Due to missing interconnections and the difficult political status, Taiwan has been excluded from this case-study. In total, 33 nodes were considered in the model.

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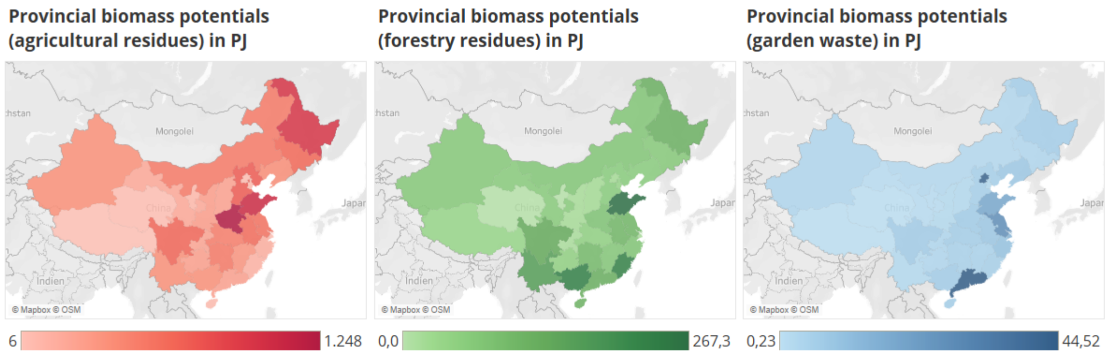
[2] The final model calculation used about 75 GB of RAM for each scenario and sensitivity run and took about 6-7 days calculation time.

Most meta data on China's demographic, economic, and industrial situation, including historic population growth, energy consumption by sector, energy composition, and fossil fuel deposits are publicly available and provided by the National Bureau of Statistics of China (NBS) (National Bureau of Statistics of China (中华人民共和国国家统计局) 2019).

Cost-assumptions, efficiencies, and lifetimes of most technologies are stated in Burandt, Löffler, and Hainsch (2018). The newly included technologies for the industry are based on Fraunhofer ISI et al. (2016). Hourly capacity factors of solar PV, wind, and heat pumps were calculated based on a 50x50km grid of *renewables.ninja* (Pfenninger and Staffell 2016) from the meteorological year of 2015. The resulting data-points have been ordered in three categories for each province. Afterwards, the average for each province and each category has been calculated and included in the model. In order to take account of the limitations and linearity of the model, the hourly capacity factors for RES stay constant over the years. Hence, no increasing efficiencies for PV are being accounted for. Also, the amount of calculated time-steps has a direct effect on the installed storage capacities, which are reduced according to their fraction of a year. Overall, possible over-estimations of renewable energy sources, heat pumps, and storages due to the rather rough timely resolution are reduced through the previously mentioned measures. Potentials of solar PV and wind are taken from He and Kammen (2014, 2016).

Biomass potentials have been adopted from Jiang et al. (2012), Shi et al. (2013), and Zhang, Zhang, and Xie (2015) and are displayed in Figure 5.2 and Table 5.1.



**Provincial biomass potentials (agricultural residues) in PJ**

**Provincial biomass potentials (forestry residues) in PJ**

**Provincial biomass potentials (garden waste) in PJ**

Figure 5.2: Overview of available biomass potentials (in PJ) of the different considered types in GENeSYS-MOD China. Own illustration based on data from Jiang et al. (2012), Shi et al. (2013), and Zhang, Zhang, and Xie (2015)

Table 5.1: Biomass potentials in GENeSYS-MOD China compared to other studies assessing biomass potentials in China.

| Type | Source | Value (EJ) |
|---|---|---|
| Agricultural residues | Jiang et al. (2012) | 11.71 |
| Garden waste | Shi et al. (2013) | 0.26 |
| Forestry residues | Zhang, Zhang, and Xie (2015) | 2.55 |
| **Total** | | **14.52** |
| Theoretical potential | Schueler et al. (2013) | 38.6 |
| Technical potential | Schueler et al. (2013) | 9.8 |
| Theoretical potential (2050, BAU) | Gao et al. (2016) | 17.32 |
| Theoretical potential (2050, NOCCS) | Gao et al. (2016) | 21.64 |

### 5.4.2 Scenario analysis

This study looks at the effect of different carbon budgets on the Chinese energy system. Therefore, the main scenarios that where analyzed impose these different budgets. To reflect the global and regional ambitions of reducing GHG emissions, we introduce a *Paris Agreement* scenario, which features a total carbon budget of 293.184 $GtCO_2$ from 2015 onwards and correspondences to a 2 ° pathway. This scenario is compared to an *Ambitious* scenario with only 115.081 $GtCO_2$ (a 1.5 ° pathway) and a *Limited Effort* scenario. The latter has no assigned $CO_2$ budget and serves as a benchmark for the other scenarios. The budgets for China were calculated using the corresponding global budgets from IPCC (2018). As there are currently no direct binding $CO_2$ targets for any country, allocating the global budget is possible in multiple ways. Possible indicators are the gross domestic product (GDP), population, or emissions. In regard of allocating a global budget by emissions, a differentiation between historic or current emission is most common. In a study analyzing Europe, Hainsch et al. (2018) showed that allocating $CO_2$ to European countries by using the current emissions is closest to an optimal allocation used by a central planner with perfect foresight. Therefore, we are using China's current emissions (from the year 2015) as key indicator to calculate the share of the global budget it is allowed to emit. Changing the indicator for allocation to GDP would decrease China's budget by 33%; an allocation by population by 47%.

All scenarios have a fixed base year of 2015 and planned and commissioned power plants are equally included in all scenarios. The targets of the current FYP of the Chinese government are included as boundaries in the model until 2020. Also, future outlines, as, for example, political efforts of increasing electric-vehicle transportation in city-states (i.e., Beijing, Shanghai) are also considered in the modeling work. Furthermore, all scenarios are calculated with and without the possibility to invest in CCTS due to the uncertainty of its technological availability. Regarding the macroeconomic assumptions, all scenarios share the same base-line. The demands for each fuel per province were obtained from National Bureau of Statistics of China (中华人民共和国国家统计局) (2019). Hereby, we allocated the demand of the different industrial branches to their corresponding temperature-range[3]. The demand growth for each different sector until 2050 was obtained from the 2017 World Energy Outlook (International Energy Agency 2017), which has a particular focus on China.

### 5.4.3 Model calibration and validation

The model has been calibrated to the base-year 2015. Capacities and production in the sectors electricity, industry, and buildings are fixed for the base year. For the transportation sector, the final energy demand and modal shares are fixed. The calculated results of the power sector were compared to similar studies by He et al. (2016) and Breyer et al. (2015) to find possible flaws.

### 5.4.4 Model characterization and limitation

As a pure techno-economic bottom-up model, GENeSYS-MOD lacks features of macroeconomic models. Hence, a strong dependency on assumptions regarding growth (e.g., GDP, population) can be observed when utilizing the model. Also, technology development is set exogenously, and thus the results depend on given cost-estimates. The past has shown that especially RES and storages were highly underestimated, as depicted by Metayer, Breyer, and Fell (2015) and Mohn (2020). We researched all recent literature and interviewed experts to achieve realistic cost estimates. For a broader picture of the whole energy-economic system, linking of bottom-up techno-economic and top-down macroeconomic models is needed in future works, as suggested by Crespo del Granado et al. (2018). This is especially needed for varying macroeconomic parameters per scenarios as these parameters (i.e., GDP) naturally change with deployment of different technologies. Still, a primary challenge of linking top-down to bottom-up models is be the inconsistency in behavioral assumptions, treatment of temporal resolution, sectoral aggregation, or regional coverage.

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[3] E.g., steel-making and aluminum production need temperatures of more than 1000°C, whereas the (non-electricity) energy demand for food-production was allocated to the low-temperature range.

Also, future analyses have to look at other pollutants apart from $CO_2$, as especially methane leakage becomes an essential factor when coal is replaced by natural gas to reduce emissions (compare Alvarez et al. (2018)). This is, however, not accounted for within this paper and would likely reduce the role of natural gas.

Furthermore, the model assumes an omniscient social-optimal planner and hence neglects local actors and barriers mentioned in the paper. Nevertheless, China's consequent FYPs, from a central planners perspective, have proven to be a particular case for China, compared to other countries, when applying optimization models (compare Section 5.6).

Additionally, the years and sectors are all calculated with an integrated approach until 2050 with perfect foresight. This integrated approach leads to new insights about the optimal use of resources in certain sectors, but neglects market- and concurring effects. Nevertheless, the multi-sectoral approach utilized in this paper generates more insights about the role of sector coupling and future developments of the whole energy system than pure power market models.

Furthermore, although significant model improvements regarding possible over-estimation of RES have been undertaken, the model still lacks a full hourly resolution. However, Welsch et al. (2014) compared an enhanced version of OSeMOSYS to a full hourly TIMES model and showed that the results only differ slightly. Overall, we believe that the modifications of the version of GENeSYS-MOD in this article allow for a good qualitative analysis to present a low-cost decarbonization pathway given general computational limitations (e.g., model size, computation time, data restrictions). An alternative to using a reduced time-series would be using representative hours instead. A notable example for generating representative days for an application in long-term models would be the algorithm presented by Nahmmacher et al. (2016). They propose a hierarchical clustering algorithm for obtaining representative days with different hourly aggregation and conclude that using six representative days with eight time-slices per day (every 3 hours aggregated) are sufficient for analyzing long-term strategies with their model for Germany. Therefore, future works with GENeSYS-MOD focusing on this region could also compare the application of representative hours with reduced and full hourly time-series.

Lastly, we want to point out that the model results should not be interpreted as forecasts, but as a source of valuable insights to transform China's energy system in line with the agreed upon international climate goals. This paper concentrates only on the development needed for complying with the Paris Agreement within the time-frame until 2050. As this time-frame is very ambitious, developments after 2050 have to be considered in future modeling works.

## 5.5 Impact of $CO_2$ budgets on the Chinese energy system

This section presents the main results of the different scenarios and sectors. As shown in Figure 5.3, the application of a $CO_2$ budget has a notable impact on the shape of the power transformation in China. The need for electrification in interlinked sectors leads to a vastly increased demand for electricity. This demand will primarily be fulfilled by the substantial introduction of renewable energy sources like onshore wind and solar PV. Even throughout the *Limited Effort* pathway, solar PV will take a significant role. Especially in north-eastern China, this can be traced back to high regional insolation with an overall projected decrease in capital costs. Only in the *Ambitious* scenario, breakthrough-technologies, such as methanized synthetic gas or hydrogen ($H_2$) are used in the power sector.

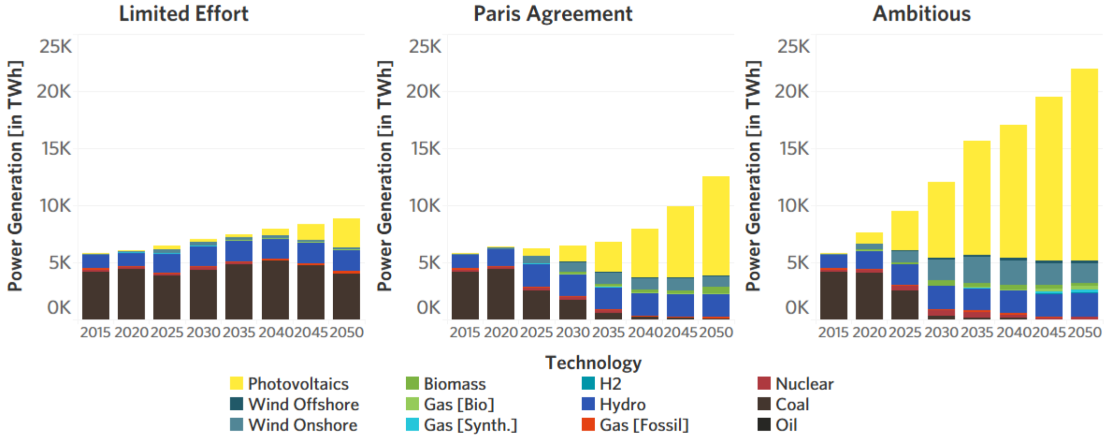

Figure 5.3: Comparison of yearly power generation by technology in TWh in different decarbonization pathways. With a more limited $CO_2$ budget, a phase-out of coal in the power sector and increasing electricity demand due to sector-coupling can be observed. Source: Own illustration.

Even under strict $CO_2$ budgets, more costly climate change mitigation technologies such as CCTS only play a minor role. Overall, the need for electrification under a strict $CO_2$ budget leads to a doubling of the final electricity demand. In the *Ambitious* scenario, the power produced by coal-fired power plants needs to be vastly reduced by 2025 to meet the climate target of 1.5 °. This phase-out will imminently result in large amounts of stranded assets, as most of the existing coal capacities in China have been newly constructed or recently modernized (Fei 2018). In general, large investments in solar PV plays a primary role in reaching the ambitious targets of the Paris Agreement. More significantly, the high degree of electrification to stay below 1.5 ° results in even higher additions of solar PV. Also, onshore wind sees more deployment in the the *Ambitious* scenario compared to the other scenarios. In the model results, the large variability and intermittency of renewables is mostly covered by inter-regional trade instead of large investments into storage technologies.

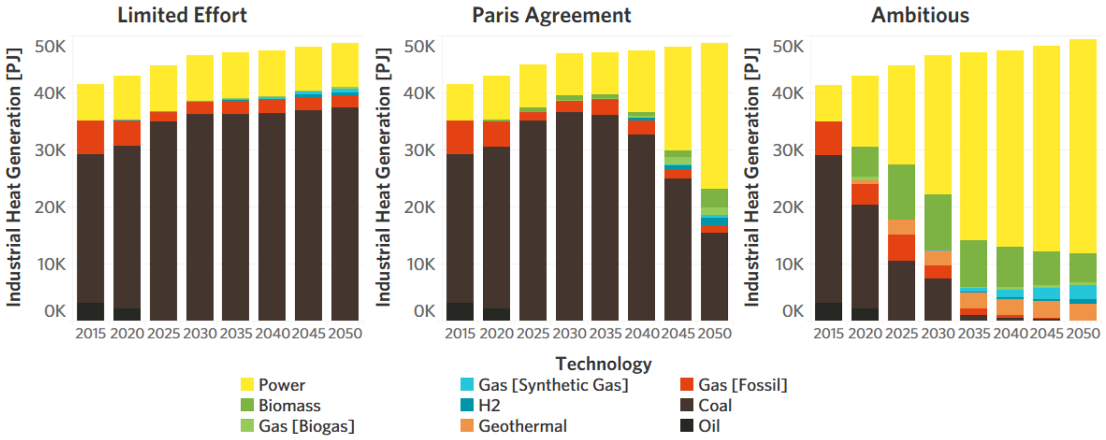

Figure 5.4: Yearly industrial heat generation in PJ per technology and scenario. Even under a compliance to the Paris Agreement, coal will keep its dominant position in the Chinese industry. Source: Own illustration.

Second to the power sector, the industry sector faces significant changes after applying a $CO_2$ budget (see Figures 5.4 and 5.5). Without any limit, coal still keeps the predominant role in the industry sector, as seen in Figure 5.4. Only in the more ambitious scenarios, the usage of coal declines throughout the periods. The strict limit in the *Ambitious* scenario leads to a nearly complete phase-out of coal in the industry sector by 2050. 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 in decarbonizing the industry sector. Overall, as seen in the *Ambitious* scenario, biomass together with hydrogen and methanized synthetic gas are key to decarbonize the industry sector. Nevertheless, a large degree of electrification is required, which is most cost- and emission-efficient when the power sector is already decarbonized. To reach the targets of the Paris Agreement, coal can still play a primary role within the industry sector, as most of the GHG reductions are achieved in the power and transportation sectors. On the other hand, slower developments in the power system can be offset by more ambitious measures in the industry or buildings sector.

In general, the buildings sector (compare Figure 5.5) sees a reduction in the use of conventional energy sources in all scenarios. Still, conventional residential heating by coal and natural gas plays a significant role in the *Limited Effort* and *Paris Agreement* scenarios. In those two scenarios, electrification takes place at a later time, when price and emission intensity of electricity decrease due to the introduction of more renewable energy sources to the power system. Under a very strict $CO_2$ budget, a substantial increase in capacities of biomass- and hydrogen-based heating, combined with a phase-out of conventional energy carriers lead to a decarbonized buildings sector from 2040 onward. In general, the increase of electrification in the residential heating sector does not increase significantly in all scenarios. Overall, decarbonization targets in this sector are mostly achieved by shifting to gas-based energy carriers (first natural gas, later bio- and synthetic gas).

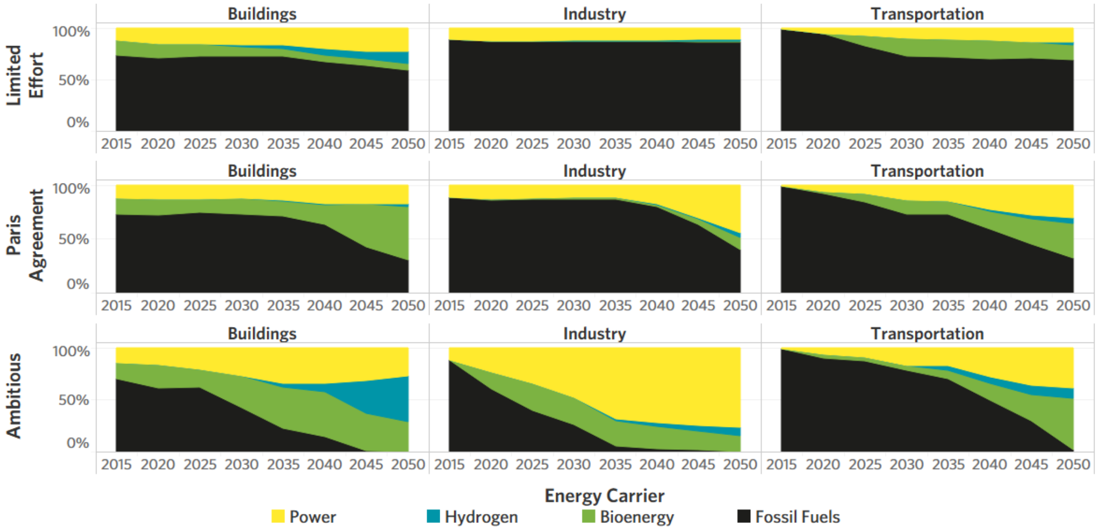

Figure 5.5: Shares of consumed energy in percent of total consumption in different sectors and scenarios. The industry sector will be the most impacted energy consuming sector when applying a $CO_2$ budget. Source: Own illustration.

In the transportation sector, petro-fuels still play the primary role in the *Limited Effort* scenario. Only under stricter $CO_2$ budgets, electrification and large-scale introduction of biofuels pose alternatives to conventional transportation. Again, biomass and biofuels are very flexible fuels for a decarbonization of this sector. Moreover, hydrogen-based transportation can be observed in the *Paris Agreement* and *Ambitious* scenarios.

Overall, the least cost decarbonization pathway for the *Ambitious* scenario leads to an energy system based on nearly 100% RES. In reverse, targeting an energy system based on 100% RES for 2050 can pose a possible way for China to stay well-below 2 ° and even reach a 1.5 ° goal. The overall possibility of a 100% renewable energy system has already been assessed in studies by Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017), Breyer et al. (2015), Brown et al. (2018), or Bogdanov et al. (2019) (compare Section 5.3). Nevertheless, those studies only have a small focus on sector-coupling and deep decarbonization of the complete energy system and do not offer a detailed representation of regional characteristics of China as presented in this paper.

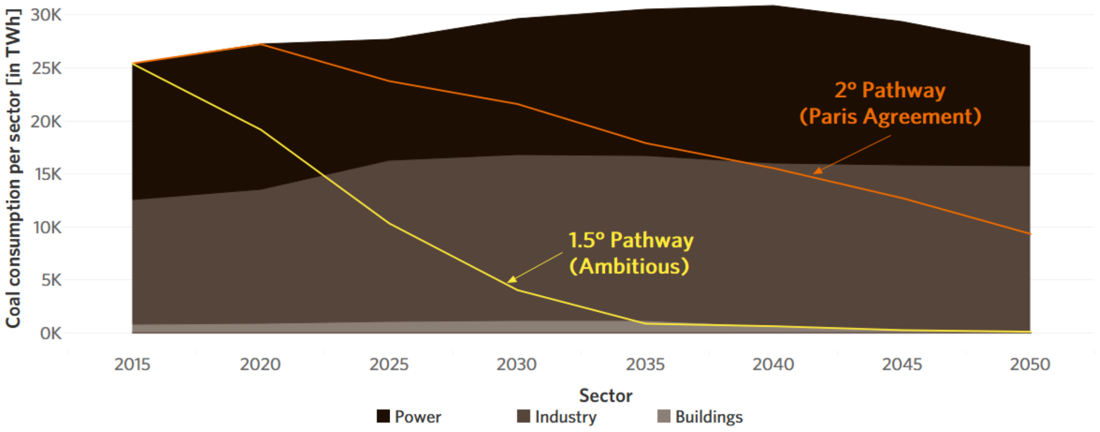

Figure 5.6: Coal consumption in TWh per sector in the *Limited Effort* pathway with coal consumption of other pathways as comparison. Under strict $CO_2$ budgets, the usage of coal needs to be reduced. Source: Own illustration.

While coal undeniably dominates the power and industrial sectors today, applying strict climate targets require a reduction in coal usage throughout all sectors. In the *Paris Agreement* scenario, the peak of coal consumption is to be expected in 2020 (compare Figure 5.6). Also, as previously pointed out, to reach the targets of the *Paris Agreement*, coal usage has to be reduced extensively, but it can still play a role in certain sectors. Contrary, the *Ambitious* scenario implies an even earlier decrease to comply with its very strict $CO_2$ budget. Even the *Limited Effort* scenario results in a plateau of coal consumption in 2040, followed by a slowly reduced demand due to the projected cost-competitiveness of renewable energy technologies and the accompanying decrease in electricity price. Overall, the target of the Chinese government to peak emissions in 2030 is, therefore, not ambitious enough to stay in line with a global target of 2 ° and below.

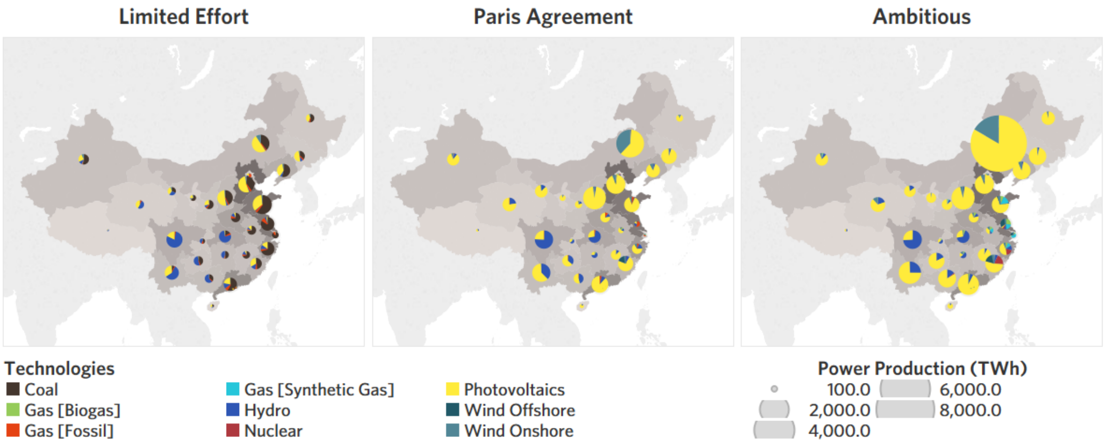

Figure 5.7: Regional power production shares in 2050 in the different pathways. Provinces with high demand are highlighted with darker background color. Grid extension and power production outside of demand centers will likely increase by applying a more limited $CO_2$ budget. Source: Own illustration.

Looking at the regional distribution of power generation shares (compare Figure 5.7), the decarbonization of the power system in China will require substantial grid extension measures (nearly doubling the total power transmission capacity from 2020 until 2050 in the *Paris Agreement* scenario). This can be traced back to the regional disparity of resource distributions. Being a region with high irradiation, Inner Mongolia will become the dominant power-generating province in China. He et al. (2016) present similar findings. Also, the large regional extension of China enables the regional power trade to balance out the variability of renewables in the more ambitious scenarios. Still, this significantly increases the need for power grid extensions. Also, the regional disparity in the availability of biomass results in a significant increase in biomass, hydrogen, biogas, and synthetic methane trading in the *Paris Agreement* and *Ambitious* scenarios.

Additional sensitivity analyses have been carried out, looking at the variety of different cost-assumptions. In general, the most significant drivers in the *Paris Agreement* and *Limited Effort* scenarios are costs of storages, solar PV, and coal. Costs-assumptions have little to no impact on the *Ambitious* scenario. Another significant driver for the results of the scenarios with a $CO_2$ budget are the potentials of solar PV and wind. Especially a higher availability of solar PV leads to decreased grid extension and higher utilization of PV, even in the *Limited Effort* scenario. The results of the sensitivity analysis also show a significant impact of final energy demand projections on the development of the energy system. Lastly, the impact of CCTS was comparably small with only some utilization in the high-temperature industry sector.

Compared to other studies targeting the transformation of the Chinese energy system, an advantage of including other sectors in the power system analysis, as well as a higher regional aggregation can be shown. Compared to the recent results by J. Liu et al. (2019), a similar peak of coal consumption in the *Paris Agreement* scenario compared to their *C2020-renw* scenario can be seen. Contrary, the *Ambitious* scenario needs even further emission reductions as presented in their paper. This is due to the different modeling approaches deployed. Whereas J. Liu et al. (2019) analyze the effect of different peaking-periods for the Chinese power system, we apply $CO_2$ budgets to all sectors of the energy system.

The optimal long-term generation and transmission structure of China’s electricity system is analyzed by Zhang, Ma, and Guo (2018). Here, they assume a strong increase in power demand across most regions (roughly an increase by 70% compared to 2015). Although being an important paper with their analysis, they still neglect the strong impact of sector-coupling and electrification on future power demands. As shown in the work presented here, the need for deep decarbonization (i.e., within the *Ambitious* scenario) leads to a substantial increase in power demand. The *Ambitious* scenario sees a 400% increase between 2015 and 2050. On the other hand, the electrification of transport and industry in the Paris Agreement only accounts for an increase of 110%. Finally, without any efforts to decarbonize other sectors, the power demand will increase even less than projected by Zhang, Ma, and Guo (2018). Overall, this highlights the importance of future power system models to incorporate other sectors with their corresponding sector-coupling and electrification potentials.

He et al. (2016) analyzed various scenarios with different demand projections. Although no inter-sectoral effects are included in their analysis, the deployed scenarios show similar trends as the results presented in our assessment of decarbonization pathways. Again, due to our multi-sectoral approach of modeling the Chinese energy system, we see different demands than projected in their scenarios and have an improved assessment of the need for electricity under different decarbonization pathways. Still, we conclude similar findings regarding the need for increased transmission structure and the importance of the Inner Mongolia province for the decarbonization of the Chinese energy system.

Lastly, assessing the additions and enhancements of GENeSYS-MOD included in the version presented in this paper, please refer to Figure 5.8 and 5.9.

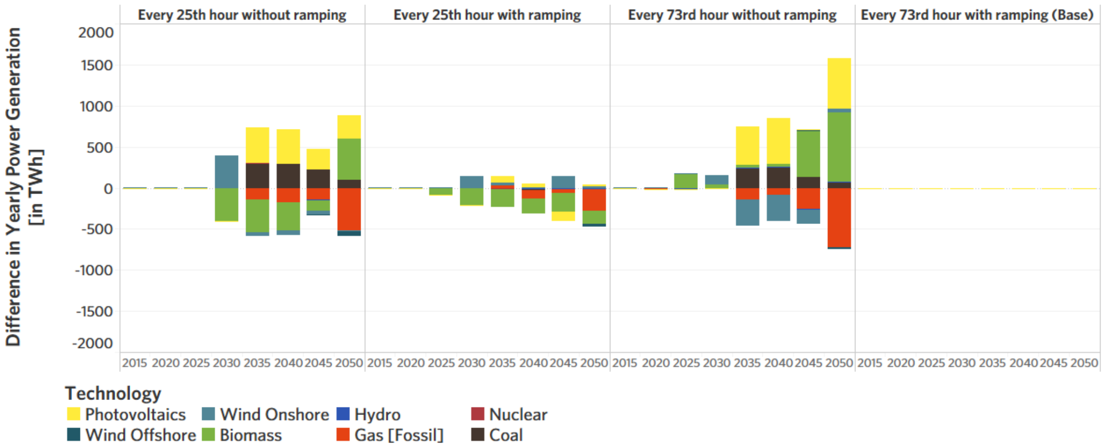

Figure 5.8: Difference of power production per year and sensitivity for an artificially aggregated Chinese power system compared to the base scenario. Smaller time-series than those used for the main scenarios only have small effects on the results. Source: Own illustration.

In Figures 5.8 and 5.9, four different sensitivities are presented for an artificially aggregated Chinese region for the *Paris Agreement* scenario[4]. For this sensitivity analysis, trade routes between the provinces, as well as regional different renewable potentials have been omitted for more comparable results.

Figure 5.8 presents the difference between the sensitivities in the yearly power production for this aggregated region. The sensitivity scenario calculating every 73rd hour with ramping constraints was used as a baseline. As shown in this Figure, the reduction from every 73rd to every 25th hour for the selection of the final time-series does not significantly impact the results, especially in the first years of the modeled period. Deactivation or activation of the newly added ramping equations (see Section 5.4), on the other hand, changes the results. For the yearly 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. A more significant change for adding the ramping constraints can be seen in the yearly dispatch, compare Figure 5.9.

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[4] All demands, potentials, and capacities are summed up and the load per time-slice and capacity factors have been averaged.

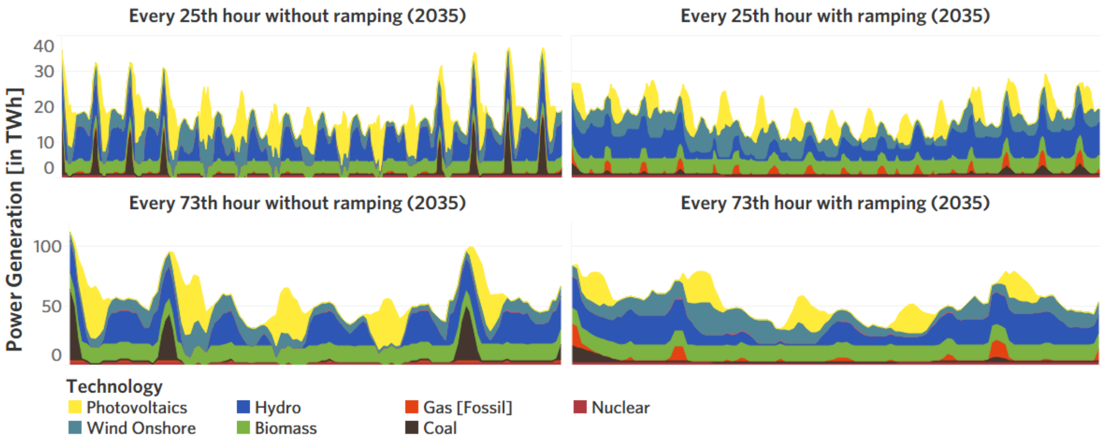

Figure 5.9: Yearly dispatch in different sensitivity assessments. Without ramping constraints, significant peaks in activating and deactivating of nuclear, coal, and biomass can be seen. Source: Own illustration.

Overall, the impact of the ramping constraints has mostly an effect on baseload technologies. Without these constraints, nuclear, coal, and biomass generation technologies can completely activate or deactivate their full capacity from one hour to another. This leads to significant peaks in the generation of said baseload technologies. In systems with high shares of renewables, the removal of ramping constraints decreases the need for storages and reduces the amount of curtailed energy.

Finally, assessing the importance of highly detailed regions is highlighted by comparing Figures 5.8 and 5.3. The need for flexibility in the power system is mostly covered by the different regional availability of renewable energy source (mostly solar PV). Also, Biomass is used to decarbonize the transportation and residential sectors and not in the power sector due to the implemented boundaries of overall usage. The artificially aggregated Chinese region presented in Figure 5.8 has an overall reduced need for power-, biomass-, and coal-trade between the regions and thus reduced costs and higher availability for those energy carriers. Although this phenomenon can be offset by a more detailed regional aggregation with weighted averages of capacity factors and hourly load, the effect of balancing the power grid through the trade of electricity can only be captured with a high regional resolution.

## 5.6 Barriers for a decarbonization of the Chinese energy system

Despite displaying enormous potentials of RES and an urgent need to decarbonize its energy system to stay in line with the Paris Agreement, China will face a variety of barriers, challenges, and obstacles.

Present-day China still suffers from high social inequality and poverty in various regions, as well as economic underdevelopment, despite the booming industrial centers, conglomerated in eastern, coastal regions. Incisive environmental targets, which allegedly restrict economic development, can, therefore, be difficult to explain to the local society, whose private welfare is often highly dependent on a single and emission-intense, industrial, local enterprise. Another aspect regarding societal opinion and barriers is the change of behavior within the Chinese culture, with increasing levels of prosperity, especially in industrial centers. Following the model of western countries, many Chinese strive for a modern and comfortable lifestyle with a stronger focus on consumption (compare Wang, Wang, and Zhao (2008)).

In public opinion, reducing emissions and the compliance to strict environmental restrictions is linked to consumption waivers and an obstruction to personal development. This opinion displays a significant lack of public information campaigns to show the importance of combining economic growth on all social levels with the needed emission reduction.

This can be seen by the obstacles that the Chinese government faced trying to decarbonize the heating sector by replacing coal with gas as a heating source between 2016 and 2017.[5] Also, as China's source for heating has largely been coal, a fuel-switch to gas would imminently result in a higher dependence on gas and liquid natural gas (LNG) imports from Russia and the USA, see Dong et al. (2014) and 李春莲 (2018). Thus, concerns about energy security related issues occur. With import shares of up to 39 % in 2017, this will significantly strain the national pipeline infrastructure and limited storage capacities. On the population side, especially elderly people in rural areas were met with difficulties in a transformation to gas based (cooking) facilities.[6]

On the policy side, considering China's division of tasks on a national (policy making) and provincial (policy implementation) level, inconsistent and relaxed implementation of policies like the emission trading system on a provincial level may deflect their initial purpose, as depicted by Duan and Zhou (2017). Furthermore, the previous methods for ensuring

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[5] See https://www.reuters.com/article/us-china-pollution-gas-heating/chinas-northern-cities-face-soot-free-winter-with-gas-revolution-idUSKCN1C72VW; last accessed 25.04.2021.

[6] See https://www.chinadialogue.net/article/show/single/en/10964-China-softens-approach-to-home-heating-switch; last accessed 25.04.2021

the implementation of policies on a local level may have proven to be effective in the past, but it might be problematic when implementing environmental policies, as these are characterized by time lags, as shown by Kostka and Hobbs (2012) and Kostka and Mol (2013). Thus, local leaders might not see an incentive on the short term of the deployment of environmental policies. Hence, inefficiencies and delayed implementations on a provincial level might occur. As China's FYP targets are only binding within the short term, the Chinese energy transformation is highly dependant on the current agenda of the ruling Communist Party of China. As measurements are initiated and coordinated on a governmental level, investments into renewable energy technologies driven by the market are missing.

While China's shift towards green, sustainable energy production and consumption, as well as choices regarding the economy, are primarily initiated and driven by the national government, the demand of the Chinese people for RES is slowly increasing. However, private companies and institutions leading the energy transformation are still to emerge, and incentives for the private sector need to be developed. This shows that the national target is only achievable when local entities understand the necessity for decarbonization and no disadvantages occur for the local actors.

## 5.7 Recommendations

China is and will be one of the main drivers for the transformation of the global energy system. While being the world's second-largest economy and the largest emitter of greenhouse gases worldwide, China has committed itself to fight climate change and to reduce its consumption of coal with their NDCs. Large shares of renewable power generation capacities have been installed in China in recent years, as depicted in Table 5.2, whereas the installment of new coal power plants decreased.

| Capacity in GW | | | | | | |
|---|---|---|---|---|---|---|
| Technology | 2015 | 2016 | 2017 | 2018 | 2019 (Q1) | Change '15-'19 |
| Thermal | 1005.54<br>(67%) | 1060.94<br>(66%) | 1106.04<br>(64%) | 1143.67<br>(62%) | 1150.28<br>(60%) | +14% |
| Hydropower | 319.54<br>(21%) | 332.07<br>(20%) | 341.19<br>(20%) | 352.26<br>(19%) | 354.86<br>(19%) | +11% |
| Solar | 42.18<br>(3%) | 76.31<br>(5%) | 130.25<br>(7%) | 174.63<br>(9%) | 179.83<br>(9%) | +326% |
| Wind | 130.75<br>(9%) | 147.47<br>(9%) | 163.67<br>(9%) | 184.26<br>(10%) | 217.88<br>(12%) | +67% |

| Generation in TWh | | | | | | |
|---|---|---|---|---|---|---|
| Technology | 2015 | 2016 | 2017 | 2018 | 2019 | Change '15-'18 |
| Thermal | 4186.80<br>(76%) | 4327.32<br>(74%) | 4587.70<br>(74%) | 4923.10<br>(73%) | - | +18% |
| Hydropower | 1111.70<br>(20%) | 1174.88<br>(20%) | 1194.70<br>(19%) | 1232.90<br>(18%) | - | +11% |
| Solar | 38.50<br>(1%) | 66.523<br>(1%) | 117.80<br>(2%) | 177.50<br>(3%) | - | +361% |
| Wind | 185.30<br>(3%) | 240.86<br>(4%) | 304.60<br>(5%) | 366.00<br>(5%) | - | +98% |

Table 5.2: Capacity in GW and yearly generation in TWh of main electricity generation technologies in China. The share of conventional, thermal, power generation capacity is decreasing over the last years with substantial amounts of renewable energy sources added each year. Data source: China Electricity Council ()

In the period from 2015 to the first quarter of 2019, 145 GW of conventional thermal generation capacities have been added to the Chinese power system. In the same period, around 260 GW of renewable energy sources have been installed, not including biomass and geothermal assets[7]. This increase in generation is also reflected in the actual yearly power generation, where the share of renewable technologies grows steadily.

Still, China has to push for additional efforts to reach their own NDCs, and even more to emerge as a leading country of the global low-carbon transformation. The results in this paper indicate that decarbonization of the industry and buildings sector is mostly depending on the power sector being carbon-free until 2050. Also, the decarbonization of the trans-

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[7] The yearly and quarterly reports of the China Electricity Council do not include information on these technologies.

portation sector has made progress but still needs to improve to meet all climate targets. With the ongoing addition of new coal-fired assets, electrification and decarbonization of the industry sector has to be promoted further, if the global target of the Paris Agreement is taken seriously. Also, the target of China's NDC of peaking emissions in 2030 is not compliant to a global $CO_2$ budget corresponding to the Paris Agreement. Targets for renewable generation and supporting actions in all sectors should be considered to comply with the Paris Agreement. Using different allocation schemes for the global $CO_2$ budget, as outlined in Section 5.4.2, would further decrease the available budget for China. This would, in turn, create the need for even higher ambitions to comply with the Paris Agreement.

Also, the time-frame until 2050 highlights the very ambitious efforts needed for complying with the Paris Agreement. With more postponed actions in the first half of the $21^{st}$ century, a view at the second half until 2100 is needed. Still, significant investments into renewable energies, energy efficiency, and promoting electrification of non-power sectors are required.

Furthermore, the current importance of local actors imposes social, political, and economic barriers for a successful transformation of the Chinese energy system. Hence, it is critical that these barriers have to be tackled by the Chinese government through interaction with stakeholders. Furthermore, to mitigate local resistance against a low-carbon transformation, additional incentives for private companies, institutions, and individuals have to be developed and introduced by the Chinese government.

## 5.8 Conclusion

In this paper, we analyzed the development of the Chinese energy system until 2050 under different $CO_2$ budgets. Our focus on sector-coupling and decarbonization pathways provide several additions for the existing literature. From a modelers perspective, we have shown that it is essential to add interconnections between sectors to have better estimations about the electricity demand increase corresponding to electrification and other decarbonization and sector-coupling measures. Also, a detailed regional level of aggregation is needed for assessing the power system balancing effects of inter-regional power trade.

The usage of $CO_2$ budgets leads to following insights about the Chinese energy system: Firstly, coal usage has to be reduced drastically to comply with a carbon budget that is in line with the Paris Agreement. Furthermore, for a cost-efficient decarbonization of the industry and buildings sectors, the power sector has to be transformed first. The speed and composition of the energy transformation in the power and industry-sector are highly sensitive to different carbon budgets. Lastly, staying well below 1.5 ° will require immediate decarbonization measures in all sectors, and an introduction of breakthrough-technologies. Also, results indicate that an energy system based on nearly 100% renewable energy sources by 2050 is needed for limiting global warming to 1.5 °. Overall, the current Nationally Determined Contributions proposed by the Chinese government are not sufficient enough to comply with a global $CO_2$ budget in line with the Paris Agreement.

Further research should examine the effect of different energy demand forecasts on the transformation of the Chinese energy system. Also, including the neighboring countries would enable to measure possible synergies of international cooperation to foster a global decarbonization pathway in line with agreed on climate targets.

# Chapter 6

# Necessity of hydrogen imports for decarbonizing Japan's energy system

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This chapter is based on the single author work published in *Applied Energy* 298 under the title: "Analyzing the necessity of hydrogen imports for net-zero emission scenarios in Japan".

## 6.1 Introduction

With the Paris Agreement, the global community agreed on reducing greenhouse gas emissions in order to keep the global mean temperature increase well below 2 °C (UNFCCC 2015). In this regard, Japan also handed in their Nationally Determined Contributions (NDCs). These aim for an emission reduction of 15-17 % until 2030 (Ministry of the Environment 2016). Japan's NDCs had been lately updated and additionally aimed for a greenhouse gas reduction of 80% until 2050 with the strife to reach carbon neutrality as soon as possible in the second half of the century (Ministry of the Environment 2020). Recently, however, Japan's Prime Minister further increased this ambition by pledging that Japan will reach a net-zero emission society in 2050.[1]

For the decarbonization of its energy system, Japan introduced a variety of policy measures to restructure its feed-in-tariff system, increase electricity from renewable energy sources, and increase its overall energy security (Zhu et al. 2020). Together with the increased support of renewable energy sources, Japan also plans to establish a "Hydrogen Society" by the mid of this century. This includes a significant promotion of fuel-cell electric vehicles (FCEV), replacement of fossil power generation with hydrogen-based power generation, and fuel-switching towards hydrogen and synthetic gases in the industry sector (Ministry of Economy, Trade and Industry 2017). To fulfill the future demands for hydrogen, domestic production of green hydrogen via electrolysis is planned to be supported alongside the establishment of international hydrogen markets. In the case of global hydrogen markets, Japan aims for importing around 5-10mt of hydrogen by 2050, most of which will come from Australia (Ministry of Economy, Trade and Industry 2017; COAG Energy Council 2019). However, importing substantial amounts of hydrogen will not be a solution to the national goal of increased energy security (Nagashima 2020), as one of the biggest problems for the Japanese energy system and energy security is the reliance on large shares of imported energy carriers. Currently, the Japanese energy system is highly reliant on mostly imported fossil fuels (Ministry of Economy, Trade and Industry 2020). This results in a high share of around 87% dependency on fossil fuels on primary energy consumption. With only small amounts of domestic fossil resources, Japan has a low self-sufficiency rate of 9.6% compared to other OECD (Organisation for Economic Co-operation and Development) countries.[2] On the other hand, Japan currently has the globally second-highest

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[1] https://asia.nikkei.com/Politics/Suga-vows-to-meet-Japan-s-zero-emissions-goal-by-2050, last accessed 03.12.2020

[2] This rate determines how much of the primary energy demand can be fulfilled by domestic resources. For example, Germany has a self-sufficiency rate of around 37%, whereas the USA has a self-sufficiency rate of around 93%.

installed capacity of solar photovoltaic (PV) plants and the third most generation (IRENA 2020).

## 6.2 Literature Review

For the Japanese energy system, and more specifically the power sector, a plethora of studies is available, looking primarily at emission reduction scenarios of about 80% - 90% by 2050 (compared to 1990). In this regard, studies often promote nuclear power production and carbon capture and storage (CCS)[3] as a valid and necessary option for a decarbonization of the energy system (Oshiro, Masui, and Kainuma 2018; Kato and Kurosawa 2019; Kharecha and Sato 2019; Sugiyama et al. 2019; Fujimori et al. 2019). In this regard, Oshiro, Masui, and Kainuma (2018) assess highly increased energy system costs for reaching ambitious climate targets without the availability of bio-energy with carbon capture and storage (BECCS) within their analysis of possible transformation pathways of the Japanese energy system. In their study, even without the deployment of BECCS, large amounts of CCS technologies have to be deployed to meet international climate targets. Similarly, Kato and Kurosawa (2019) found with their modeling approach that Japan cannot reach 80% or even 90% emission reduction without large-scale deployment of CCS. Furthermore, a cross-model comparison of 80% reduction scenarios has been carried out by Sugiyama et al. (2019). As a result of this, they present that the industrial sector has a large final energy share and significant residual carbon dioxide emissions under 80% reduction scenarios, which highlights the difficulty of the decarbonization of that sector. Also looking at 80% reduction scenarios, Fujimori et al. (2019) link a computable general equilibrium (CGE) model to an energy system and power market model to assess the loss in GDP resulting from the energy transformation with different model setups. Comparing Japan and Germany, Kharecha and Sato (2019), analyze the cuts in $CO_2$ emissions after the Fukushima incident. They advocate that a prolongation of nuclear power and instead of phasing out coal and natural gas would reduce emissions even further and lead to fewer air pollution-induced deaths. However, they also show that despite the phase-out of nuclear power in Germany and Japan, total $CO_2$ emissions have been reduced due to the large-scale deployment of renewable energies.

Overall, in these previously mentioned studies, the external costs of nuclear power plants (Sovacool 2010) or historical and current cost overruns of nuclear power plants (Haas, Thomas, and Ajanovic 2019; Wealer et al. 2019) are often not discussed or neglected. Furthermore, the technological applicability of large-scale deployment of CCS is still uncertain

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[3] Also promoted as carbon capture, transport, and storage or carbon capture, transport, and sequestration (CCTS) in certain studies (Hirschhausen, Herold, and Oei 2012).

(Oei and Mendelevitch 2016; Minx et al. 2018). Additionally, there are limited geologically appropriate areas for CCS deployment on Japanese territory (Fujimori et al. 2019) and thus, scenarios without the availability of CCS should also be considered. Nevertheless, only a few studies analyze 100 % renewables in the power system in Japan, and no study is available looking at net-zero emissions in Japan without the necessity of utilizing CCS or nuclear energy. Esteban, Zhang, and Utama (2012) and Esteban et al. (2018) highlight that 100 % renewables are indeed possible with moderate demand assumptions, but will result in large-scale deployment of batteries and overall increased balancing requirements for the power system. In this regard, Neetzow (2021) shows that renewable energies are indeed able to first replace flexible generation (e.g., gas-fired power plants) and later inflexible generation (e.g., coal and nuclear). Apart from specifically looking at the Japanese energy system, 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; Bogdanov et al. 2021). Hereby, Bogdanov et al. (2019) and Ram et al. (2019) present a power system based on 100 % renewables for the whole world. They show that, in the case of complete decarbonization of the power sector, significant investments into power system flexibility are needed to compensate for the variable and intermittent nature of renewable energy sources. Also incorporating sector-coupling effects and the global energy system, Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) and Bogdanov et al. (2021) present different analyzes looking at the global energy system based on 100% renewables, also incorporating non-electricity sectors and sector-coupling effects. Both studies highlight the importance of low-cost renewable energy sources as a basis for a successful energy transformation. Furthermore, they also emphasize the importance of swift and consequent climate actions, combined with long-term strategic planning of energy and climate policies.

Regarding the importance of flexibility options for the global and Japanese future energy systems, Bogdanov and Breyer (2016) present an energy system based on 100 % renewables for the North-East-Asian region, where balancing and flexibility will be provided by the deployment of a super-grid encompassing the whole region. Thus, Japan's connection with mainland China allows for large-scale power trade to compensate for the regionally different production patterns of renewable energy sources. Similarly, Ichimura (2020) points out that increased cross-regional interconnection inside Japan can prove to be a crucial factor in balancing renewable energies.

Furthermore, flexibility for the power system can also be provided by demand-side measures. In this regard, electricity storage and system flexibility can also be provided by battery electric vehicles (BEV), which provides system-wide benefits, especially in combination with residential solar PV (Li et al. 2020). When BEVs are charged within the peak of solar PV production, the battery of electric vehicles can provide an economical way of storing excess power and later using it via vehicle-to-grid integration (Kobashi et al. 2020). However, public opinion is crucial, as local actors and citizens drive the deployment of solar PV systems in metropolitan areas in conjunction with electric vehicles. However, as Chapman and Okushima (2019) showed in their study, lower-income households in Japan are less likely to be interested in a low-carbon energy transition and might favor non-renewable energy options. Therefore, the Japanese government would need to re-distribute the costs and benefits of solar power deployment more progressively and increase subsidies in prefectures with lower incomes to deploy renewable energies effectively throughout the country (Gao, Hiruta, and Ashina 2020).

The production of hydrogen presents another cost-efficient way of providing flexibility for the energy system by storing and later utilizing excess renewable energy via electrolysis. Linking the electricity and gas networks may provide the flexible resources and necessary infrastructure to absorb the increasing renewable energy production (X. Zhang et al. 2017; Li, Gao, and Ruan 2019). Excess renewable energy can be profitable to transform to hydrogen and provide energetic benefits for decarbonizing the energy system, although significant cost barriers remain (Chapman et al. 2019). Nevertheless, hydrogen and hydrogen storages are suitable for storing excess renewable energy production for an extended period of time, and hydrogen storages by themselves pose to be economically competitive with battery storages in Japan (Komiyama, Otsuki, and Fujii 2015). When targeting net-zero emissions in the power sector, and CCS and nuclear are not available, electricity generation from hydrogen can play a significant role (Ozawa et al. 2018). In general, hydrogen can be burned in gas turbines and has the same ramping and cycling capabilities as natural gas based power generators. However, hydrogen production is still costly, and in order to decrease the costs for electrolysis, governmental incentives are necessary to increase the profitability of hydrogen systems (Tlili et al. 2019). Also, utilizing a multi-sectoral approach for analyzing hydrogen systems seems essential, as hydrogen can not only provide electricity, but energy in the industrial (i.e., as a chemical component or energy carrier), buildings, and transportation sectors. Globally, hydrogen is assumed to play a critical role in the transportation sector, especially for heavy-duty road-based transportation via fuel-cell electric vehicles in 2050, as hydrogen and hydrogen electrofuels pose a more cost-competitive alternative to biofuels (Anonymous 2016; Lester, Bramstoft, and Münster 2020; Chapman et al. 2020). Specifically, hydrogen and hydrogen-based ammonia can also provide the means to decarbonize the maritime shipping sector (Gray et al. 2021; Fasihi et al. 2021). Additionally, hydrogen could also be used in a large variety of applications in local smart grids in future energy systems for generating electricity, as energy storage, or for producing heat. However, integrating hydrogen in smart grids still faces many challenges from a demand-side and market perspective, but also from a technological side (Lin, Zhao, and Wu 2020).

In this paper, the value of hydrogen for reaching net-zero emissions without the deployment of CCS or additional nuclear generators under different assumptions regarding the prices and availability of hydrogen imports is assessed. In this research, a novel stochastic version of the open-source multi-sectoral Global Energy System Model (GENeSYS-MOD) (Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Burandt, Löffler, and Hainsch 2018; Burandt et al. 2019) is used to examine the case of Japan. Furthermore, to generate further insights about the flexibility of hydrogen in the power sector and to assess the feasibility of the results of the energy system model, a full-hourly power system dispatch model is used in conjunction with GENeSYS-MOD.

Although the modeling work of this paper is focused on the region of Japan, the findings presented in this paper can also be of interest to international policy- and decision-makers as well as energy system modelers. In general, uncertainty is widely acknowledged as a key issue for energy systems planning. However, it is often neglected in energy system models (Paltsev 2017; Yue et al. 2018). In fact, in all of the studies mentioned above analyzing either the global or the Japanese energy system, no formal techniques of uncertainty modeling have been applied, although several methods exist. Most commonly, two methods of analyzing uncertain elements to quantitative models are applied: stochastic programming (Birge and Louveaux 2011) or deterministic and stochastic sensitivity analyses (i.e., Monte-Carlo simulations) (Pfenninger, Hawkes, and Keirstead 2014; Ferretti, Saltelli, and Tarantola 2016; DeCarolis et al. 2016). This paper contributes to the existing literature gap regarding long-term energy system analyses by applying stochastic programming to address uncertainties in energy system modeling.

Furthermore, it specifically investigates the inter-linkage between ambitious climate targets and hydrogen imports, which is also an actual topic for possible hydrogen-exporting as well as future hydrogen-importing countries. Although hydrogen can play an important and broad role in future energy systems, current research often only focuses on narrow use-cases or only in certain sectors. As of now, a comprehensive analysis of hydrogen production and consumption in a multi-sectoral energy system model on a detailed technological level is missing in the literature. Especially, as the topic of net-zero emissions is gaining interest in various countries (Kobiela et al. 2020; Prognos, Öko-Institut, and Wuppertal-Institut 2020; Tsiropuolus et al. 2020).

## 6.3 Methods

For this research, the multi-sectoral open-source Global Energy System Model (GENeSYS-MOD) by Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) has been enhanced and reformulated into a multi-horizon two-stage stochastic linear optimization problem (Birge and Louveaux 2011) and has been applied to the Japanese energy system. Additionally, the results from GENeSYS-MOD are used in a power system dispatch model to check the general feasibility of the resulting power system for 2050.

### 6.3.1 Stochastic energy system model

In general, GENeSYS-MOD is a linear cost-optimizing techno-economic model based on the Open Source Energy Modelling System (OSeMOSYS) (Howells et al. 2011; Gardumi et al. 2018). GENeSYS-MOD builds upon this framework and extends its core functionalities as well as its sectoral coverage (Burandt, Löffler, and Hainsch 2018; Burandt et al. 2019). Besides the power sector, non-electricity sectors such as industrial, residential and commercial buildings, and mobility are incorporated into the model. Overall, this allows for an extensive analysis of sector-coupling aspects and assessment of electrification efforts in the future energy system.

For this analysis, the industrial sector has been extensively reformulated. Instead of the previous demands for specific heating ranges (buildings heat, low industrial heat, medium industrial heat, high industrial heat, compare (Burandt et al. 2019)), different industrial sub-sectors are now modeled in greater detail: Aluminum, Copper, Ammonia, Chlorine, Steel, Lime, Glass, and Cement production, as well as their primary intermediate products. Additionally, the buildings sector has been split into residential and commercial sub-sectors, each with their own set of technologies. In this regard, the presentation of combined heat and power (CHP) plants, as well as district heating (DH) in general, has been improved.

To add elements of uncertainty, GENeSYS-MOD has been extensively reformulated into a two-stage stochastic program with recourse (Birge and Louveaux 2011). Additionally to the changes in the technological representation, the temporal resolution has also been adjusted for a better implementation of the stochastic variables. In general, the temporal structure now follows Skar et al. (2016). In this regard, the principles of multi-horizon stochastic programming as presented by Kaut et al. (2014) are applied. Therefore, stochastic and operational uncertainty is represented by independent stochastic processes. It is also assumed that current operational decisions do not directly affect future strategic or operational decisions. This allows to isolate current operational decisions from future decisions and reduce the scenario tree's total size.

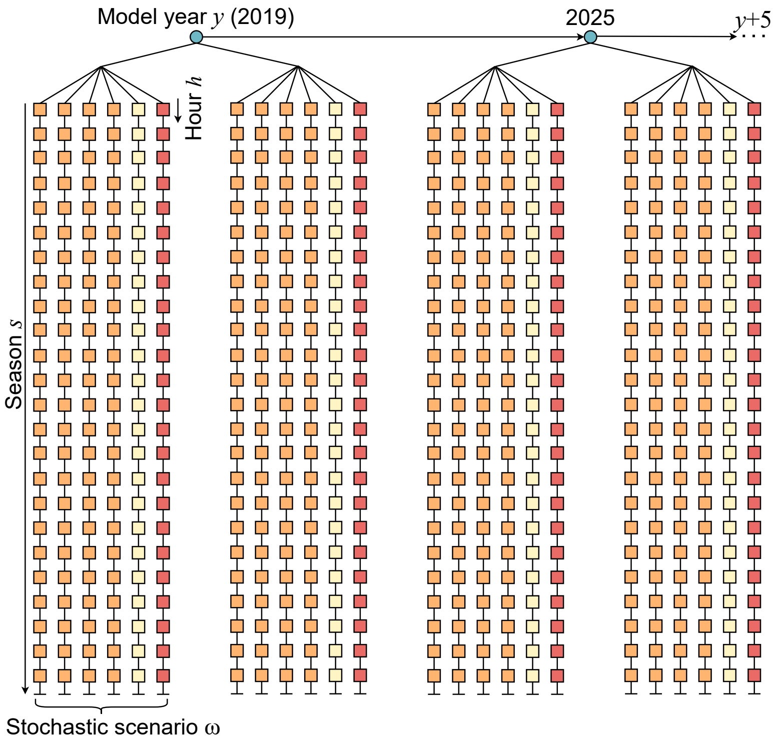

Figure 6.1: Example visual representation of the temporal and stochastic structure of the stochastic version of GENeSYS-MOD with two stochastic scenarios. Blue circles represent the model years, each of which has two stochastic scenarios associated in this example. Each stochastic scenario is divided into six seasons (four regular and two special) consisting of 24 consecutive hours (represented by orange, yellow, and red squares) each. The actual structure utilized within the model is presented in Section 6.3.1.1. Own illustration.

Yearly investment decisions represent the strategic stages. With this, perfect foresight about strategic data is assumed and strategic uncertainty neglected. Instead, each year has several stochastic scenarios $\omega$, each represented by different seasons $l$. Each year and stochastic scenario has the same amount of seasons associated. Also, each season for each scenario has the same amount of consecutive hours $h$. An exemplary visual representation of this structure is shown by Figure 6.1, whereas the actual setup used in this article is presented in Section 6.3.1.1.

In contrast to using a yearly full-hourly time-series of 8760 hours, this formulation has a largely reduced problem size. Still, it allows for a representation of short-term operation planning while representing the seasonal intermittency. Operational uncertainty is represented by uncertain hourly variable renewable infeed (i.e., solar PV, wind, run-of-river hydropower) and uncertain hourly demands. Other techno-economic parameters such as costs, fuel prices, emission budgets, and efficiencies are assumed to be strategic data.

The model was solved using different amounts of stochastic scenarios (compare Section 6.4.2). Common for all model runs, stochastic scenarios, and years is the temporal structure. Each stochastic scenario is divided into six seasons, each of which has 24 consecutive hours. The model's storage formulation has been adjusted to this new temporal structure, and only long-term storages (e.g., pumped hydro, compressed air energy storage) are allowed to store energy from one season to another.

#### 6.3.1.1 Stochastic scenario generation

The data used for the stochastic scenarios $\omega \in \Omega$ comes from a sample of consecutive hours from historical data, and all data types (e.g., solar PV infeed, residential demand, etc.) used the same sample of consecutive hours. This preserves auto-correlation and correlation between data series. The samples are randomly chosen for each season and stochastic scenario.

To generate the stochastic data, first, for each modeled year $y \in Y$ and stochastic scenario $\omega \in \Omega$, a random data year $k \in K$ is chosen (compare Algorithm 1). Data is chosen from historical data from 2010 until 2019. For each regular season $s \in S$, a random number $\theta_s^{rnd}$ between $(s-1)\frac{8760}{|S|}+1$ and $s\frac{8760}{|S|}-24$ is chosen.[4] Then, it is ensured that each season starts with the first hour of the day by calculating $\theta_s = \theta_s^{rnd} - (\theta_s^{rnd} \ mod \ 24)$. Therefore, all stochastic scenarios for all seasons start in the same hour of the day- and night-time hours are equal in all cases. For all regions, the data for the 24 consecutive hours starting from $\theta_s$ are taken as data for the season and stochastic scenario from the existing historical data $\xi_{k,r,h}^{data}$. Lastly, for each region, two special seasons with extreme cases are added. First, a season containing the 24 consecutive hours with the highest variable renewable infeed based on the chosen historic year is added, and consequently, a season with the lowest variable renewable infeed is included as well.

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[4] E.g., for a total of 4 seasons, the range for a random number for season 2 is between 2191 and 4356.

**Algorithm 1** Stochastic scenario generation

```
for $y \in Y$, $\omega \in \Omega$ do
    select random data year $k \in K$
    for each regular season $s \in S$ do
        select random number $\theta_s^{rnd} \in [(s-1)\frac{8760}{|S|} + 1, s\frac{8760}{|S|} - 24]$
        calculate $\theta_s = \theta_s^{rnd} - (\theta_s^{rnd} \; mod \; 24)$
        for $r \in R$, $h \in H$ do
            select hourly data sample $\xi_{y,\omega,s,r,h}^{sample} = \xi_{k,r,h'}^{data}$
            with $h' = \theta_s + h + 1$
        end for
    end for
    for $r \in R$ do
        add 24 consecutive hours with highest variable infeed as season $|S| + 1$
        add 24 consecutive hours with lowest variable infeed as season $|S| + 2$
    end for
end for
```

The resulting sampled data points $\xi_{y,\omega,s,r,h}^{sample}$ are then assigned their respective actual model parameters. For this research, cases of the model have been run, ranging from 1 stochastic scenario up to 5 stochastic scenarios with 4 regular and 2 special seasons each. The model itself is implemented in GAMS, and each model run has been calculated by using the commercial solver CPLEX on a high-performance cluster. For a model run with 5 stochastic scenarios, 410 GB of RAM and a calculation time of roughly 120 hours have been needed. Model runs with only one stochastic scenario represent model runs without uncertainty, as the probability for the realization of the only existing scenario is always 100%. The scenario generation algorithm was executed once before the actual model runs. Hence, cases with 5 stochastic scenarios contain the same scenarios as the cases with 4 stochastic scenarios plus 1 additional one.

### 6.3.2 Dispatch model

A full-hourly power system dispatch model has been used in addition to GENeSYS-MOD to investigate the general feasibility of the resulting power system for 2050. The dispatch model is implemented in GAMS, too, and its mathematical formulation loosely follows Schill and Zerrahn (2018). The mathematical formulation of the dispatch model can be found in Appendix E.3. In general, it is implemented as a linear optimization program focusing on generation planning in the power sector, minimizing the dispatch costs for each hour and each region. Key parameters, such as power demand for each hour, existing power generation capacities, power transmission lines, and electricity storages are obtained from GENeSYS-MOD results. In this paper, the power system dispatch model uses a linear net-trade flow formulation for power trade instead of a more sophisticated dc load flow formulation. Ramping constraints are represented in the model and considered while optimizing the hourly dispatch. Additionally, the dispatch model can generate electricity via an extremely costly *Infeasibility* technology to consistently meet the electricity demand if GENeSYS-MOD installs not enough installed capacities. Therefore, the dispatch model can always generate a feasible solution, and the results of the different model runs can be benchmarked against each other.

### 6.3.3 Key data

In this research, Japan is divided into 8 regions based on the operation area of major power companies. However, to reduce the total number of regions, Okinawa has been included in the Kyūshū region, and Hokuriku is included in the Chūbu region. Transmission capacities between these regions, as well as current network extension plans, are considered. Regional energy demand data for all sectors has been obtained on a prefectural level from the Japanese Agency for Natural Resources and Energy[5] and has been aggregated to match the modeled regions.

Hourly capacity factors of solar PV, wind, and heat pumps were calculated based on a 50x50km grid of Japan of *renewables.ninja* (Pfenninger and Staffell 2016) for the historic years 2010 to 2019. The resulting data points have been statistically classified in different categories (e.g., inferior, average, and optimal solar PV locations) and aggregated for the corresponding regions. Installable potentials of solar PV and wind power have been taken from Kojima (2012), Bogdanov and Breyer (2016) and Jacobson, Delucchi, Bauer, et al. (2017). These potentials have been compared and checked with own calculations based on average capacity factors and land utilization rates. Other technology parameters have been taken from Simoes et al. (2013), Burandt, Löffler, and Hainsch (2018), and Ram et al. (2019).

### 6.3.4 Scenario assumptions

For this paper, the main focus was on analyzing the impacts of hydrogen imports on reaching net-zero emissions in Japan in 2050. Thus, all scenarios that have been calculated aim for net-zero emissions in 2050. In this regard, negative emission technologies, CCS, and prolongation of nuclear power plants and investments into newly built generators are disabled for this analysis. Overall, 9 cases with different hydrogen import prices, ranging from 2€/kg to 6€/kg in 2050, have been considered, and one case without the possibility of importing external hydrogen. The prices for hydrogen imports start at a price of 9.5€/kg in

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[5] In Japanese: https://www.enecho.meti.go.jp/statistics/, last accessed: 21.12.2020

2019 and are linearly interpolated until the target price in 2050. This analysis does not assess the origin of the imported hydrogen, but it is assumed to come solely from renewable sources. Therefore, the carbon content of the imported hydrogen is assumed to be zero. For further sensitivity analyses, all cases have been run with and without the availability of methane pyrolysis. Despite being a promising technology to produce emission-free hydrogen, methane pyrolysis is currently not commercially available, and future development still sees specific challenges that have to be overcome before a large-scale deployment could be possible (S. Schneider et al. 2020; Sánchez-Bastardo, Schlögl, and Ruland 2020). Therefore, the results presented in this paper assume no availability of methane pyrolysis.

Furthermore, there is no limit set on the amounts of hydrogen imports, such that the model can freely choose the amount of imported hydrogen that would be beneficial from a system optimization perspective. Furthermore, a major reactivation of the nuclear reactors shut down after the Fukushima Daiichi incident is prohibited in this analysis. Nuclear power generation is limited to 2019 levels to explore the possibility of an energy system decarbonization without nuclear power generation.

The model is calibrated to the base year 2019 and runs in 5-year steps until 2050 (6-year step between 2019 and 2025). Existing and planned capacities for power generation technologies are included in all scenarios. The primary energy consumption, power production, and electricity demands in the base year have been validated by using official government statistics (compare Appendix E.2).

## 6.4 Results

This section presents the key results of this analysis starting with the results for the general energy system development in Section 6.4.1. Afterwards, the influence of uncertainty and stochasticity on the results is presented.

### 6.4.1 Energy system development in Japan

Firstly, the impact of hydrogen imports on the power system, electricity prices, general import dependency, and other industry branches is discussed. As presented in Figure 6.2, allowing hydrogen imports has a tremendous impact on the power system development. Overall, a significant shift towards renewable energy sources, such as solar PV, onshore and offshore wind, and hydropower, can be observed in all scenarios. Subsequently, fossil power generators will need to be phased out by 2050 to reach the goal of net-zero emissions.

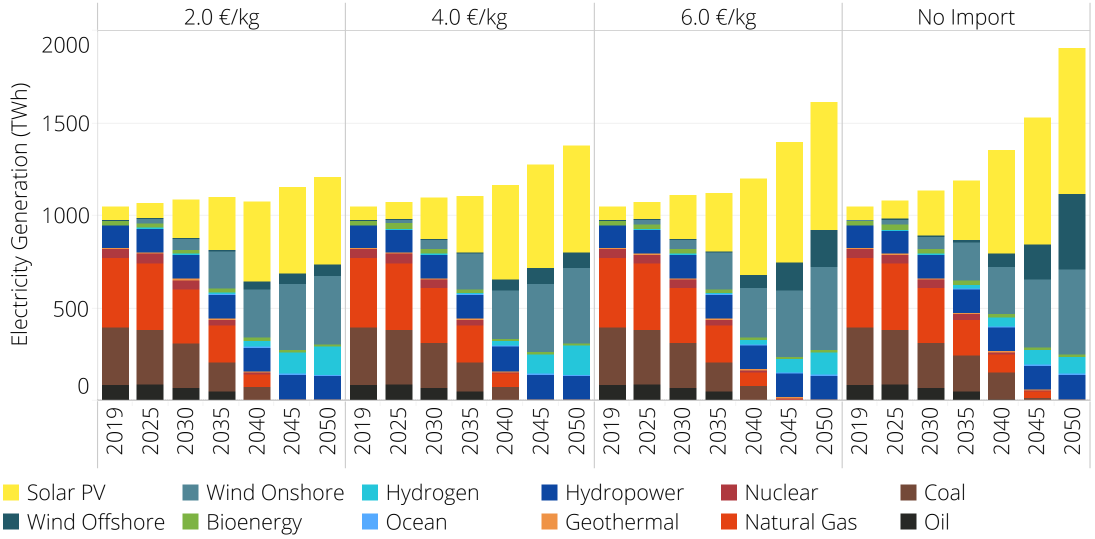

Figure 6.2: Power system development in the energy system model until 2050 with 5 stochastic scenarios. The annual results present the average of all stochastic scenarios. Own illustration.

Commonly for all cases, solar PV will become the primary source of electricity, with a power generation of 40%-45% of the total electricity production. The large amount of solar PV will be complemented by significant amounts of onshore wind power. Further baseload electricity will be provided by hydropower in all cases. However, extensive efforts to electrify other sectors or produce hydrogen from electricity have to be pursued in the case without any hydrogen imports. This results in significantly increased power demands from other sectors, and therefore the total power production nearly doubles from 2015 towards 2050 in the case without hydrogen imports from around 1050 TWh to 1900 TWh. Also, in this case, offshore wind power plays a more prominent role as opposed to the other cases, since despite being a rather costly option, it can complement the large amounts of solar and onshore wind.

Furthermore, power production from hydrogen sees differences between the cases. Although all cases utilize electricity from hydrogen to a certain degree, the importance of hydrogen for the power sector differs. With cheaply available hydrogen (2 €/kg), 12 % of electricity will be directly produced via hydrogen (150 TWh) and thus will be providing baseload. In contrast, without hydrogen imports, only 4 % (92 TWh) of electricity will be produced by hydrogen utilization. Without the possibility of importing external hydrogen, the domestically produced hydrogen will be more valuable to use in the other sectors, with batteries, seasonal storages, and increased transmission capacity providing flexibility in the power system.

Due to the large amounts of variable renewable energy sources in all cases, the prices for producing electricity will generally be lower than today's prices (compare Figure 6.3). The overall lowest levelized cost of electricity (LCOE) can be found in the case without any hydrogen imports, as large amounts of renewables and cheap domestic produced hydrogen have a positive effect on the power generation price. When hydrogen imports with a price of 2 €/kg are possible, nearly as low power generation costs can be observed in the model. Again, renewables pose a cost-efficient way to decarbonize the power system and reduce power generation prices. In this case, electricity produced from hydrogen is nearly as cost-efficient as renewable power production.

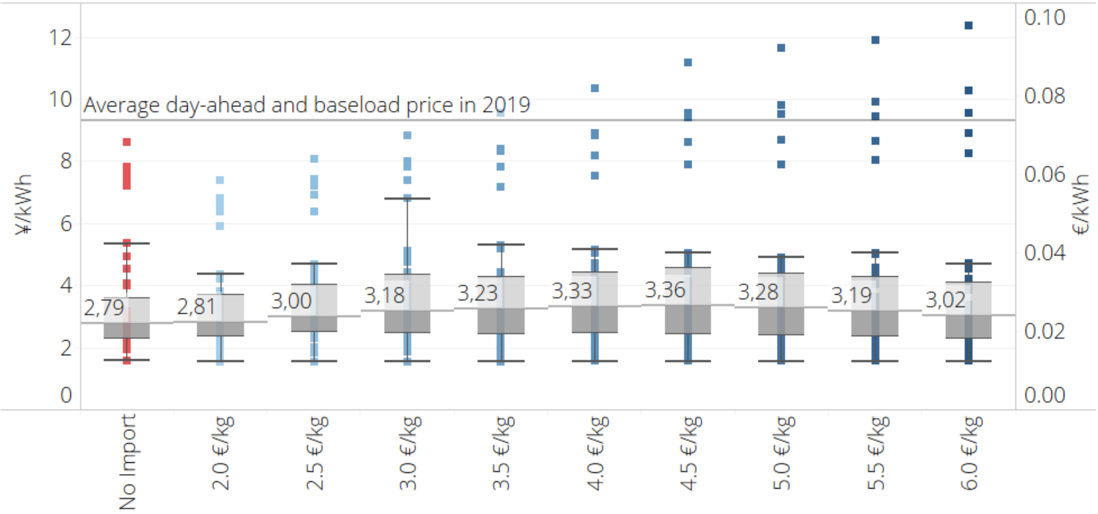

Figure 6.3: Average of annual average power generation prices in Japan for all regions and all 5 stochastic scenarios in 2050. In all cases, the topmost outlier represent the Kantō region. Own illustration.

Furthermore, hydrogen imports positively impact the average power generation prices in the Kantō region (where the metropolitan area of Tōkyō is situated). In this region, the average LCOE in the case with 2 €/kg hydrogen imports is 6.6 ¥/kWh instead of 7.5 ¥/kWh in the case without hydrogen imports. Mainly because of the limited area for renewable energy sources, this region is always relying on power transmission and electricity produced from hydrogen and hydropower. Hence, cheap imported hydrogen poses a valuable alternative for power production in heavily urbanized regions as a substitute for local renewable energy. On the other hand, the highest LCOE could be observed in cases with hydrogen imports of 4.0 - 4.5 €/kg. Here, imported hydrogen will be used in the power sector, which increases the power price, but at the same time, large amounts of hydrogen are used in non-electricity sectors. Therefore, using hydrogen in non-electricity sectors positively affects the electricity sector, as electrification in the buildings and industrial sectors is reduced and substituted by hydrogen-based technologies. Hence, a positive effect on the overall system costs can be observed, although average power generation prices are 20% higher than in the case without hydrogen imports.

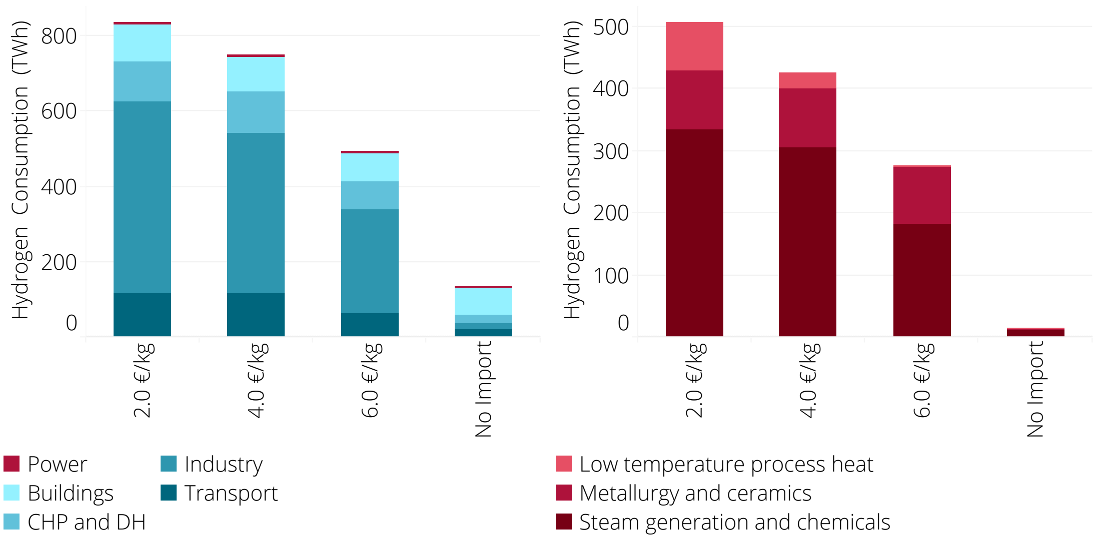

Figure 6.4: Overall hydrogen consumption (left) and aggregated industrial use (right) of hydrogen in GENeSYS-MOD in the case with 5 stochastic scenarios. Own illustration.

The usage of hydrogen across all sectors in general and specifically in the industrial subsectors is depicted in Figure 6.4. As previously mentioned, the effect on the power sector is generally minor in all cases, regardless of hydrogen import availability. In all cases, significant amounts of hydrogen will be used by dedicated district heating plants (DH) and by residential homes and commercial buildings for direct heat generation. With decreasing hydrogen import prices, the role of hydrogen in the transportation sector increases, although this primarily impacts freight transport, as passenger transportation will tend towards the usage of battery electric vehicles in the model. However, allowing hydrogen imports allows for higher usages of hydrogen, especially in the industry sector. Up to 500 TWh (roughly 12mt of hydrogen) will be used in the industrial sector alone in the case with the cheapest hydrogen imports. Overall, in this case, 19mt of hydrogen will be imported, which exceeds current governmental plans for importing 10mt hydrogen in 2050 (Ministry of Economy, Trade and Industry 2017).

Without any imports, only small amounts are used for steam generation and in the chemical sector. This amount is significantly increased the cheaper the imported hydrogen becomes available, as steam generation via hydrogen becomes the primary consumer of hydrogen. However, only with hydrogen imports, hydrogen plays a significant role in the metallurgy sector. As a result of this, the largest share is being used in the steel production sector with direct reduced iron produced via hydrogen combined with steel-making in electric arc furnaces. Second are generic high-temperature furnace appliances used in specific industrial sub-sectors (e.g., glass, ceramics, etc.). Also, alumina refineries utilizing hydrogen are used when hydrogen imports become available. In the case without hydrogen imports, the metallurgy sub-sectors will opt for direct electrification of most products (e.g., molten electrolysis, electric (arc) furnaces, etc.). When hydrogen import prices get as low as 4.0 €/kg, hydrogen will also be used in other industrial sub-sectors where low-temperature process heat is required (e.g., food production).

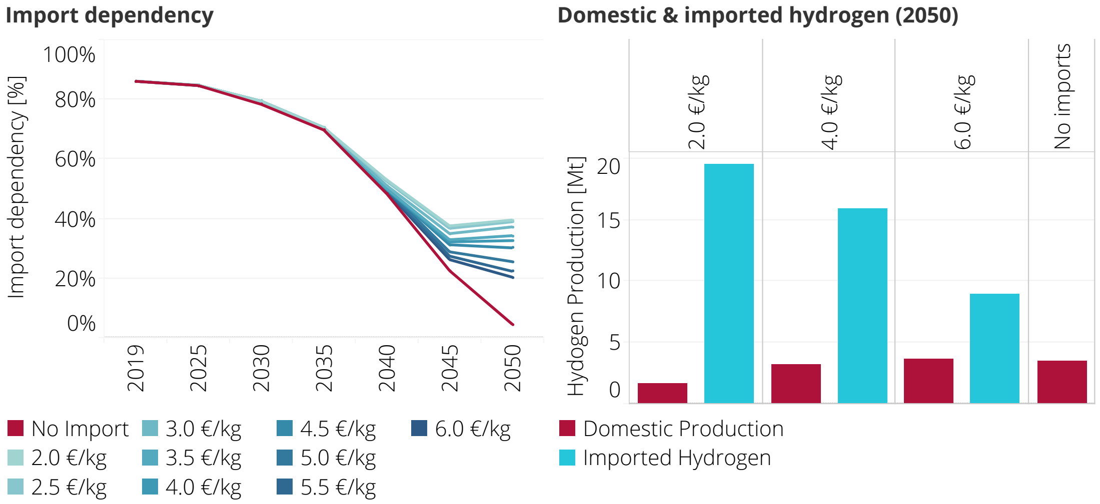

Figure 6.5: Import dependency of the Japanese energy system from 2019 until 2050 in the case with 5 stochastic scenarios. Own illustration.

Overall, importing hydrogen will also increase the import dependency of the Japanese energy system towards 2050 compared to the cases without any possibility to import hydrogen (compare Figure 6.5). Without hydrogen imports, the Japanese energy system will depend only on 4% foreign fuel imports. These fuels will be used in industrial processes, where no carbon will be embodied in the final product, and no direct emissions occur. However, when hydrogen imports are allowed, the import dependency will be around 20% to 40%. An import dependency of 40% is still significantly less than today's levels and positively impacts the Japanese government's energy security goals. However, for maintaining overall energy security with such import dependency levels, diversification of suppliers is needed. Furthermore, the scenario without hydrogen imports still sees higher overall energy security, with most energy carriers being produced domestically.

Furthermore, it can still be observed that a transformation of the energy system towards renewable energy sources, hydrogen, and electrification increases energy security. Currently, the Japanese energy system is dependent on 86-87% foreign energy supports, utilized in most of the sectors. Hydrogen imports in the model only play a role from 2035 onward, with only marginal impacts in the years before 2035. In cases with cheap hydrogen imports available, the import dependency in 2050 is slightly increasing compared to 2045. It can be assumed that the trend of importing hydrogen will either further increase or at least stay stable in the years from 2055 onward if enough global hydrogen exporting capacities exist. Import dependency levels in today's magnitude seem unlikely considering the energy system developments presented in this paper.

The accumulated model period emissions in all cases with 5 stochastic scenarios range from 20.2 to 21.4 Gt $CO_2$. Based on different metrics as presented in Table 6.1, this is still in line with a 1.5 °C compatible pathway (global emissions divided by GDP) or at least 2 °C (global emissions divided by population). However, it becomes clear that net-zero emission does not necessarily represent a well-below 2 °C compatible energy transition pathway as

Table 6.1: Remaining global and Japanese carbon budgets in Gt based on IPCC (2018). The remaining carbon budgets for Japan were obtained using different metrics.

| Approximate global warming | | Global 2018 | Japan 2019 *Population* | Japan 2019 *GDP* | Japan 2019 *Current Emissions* |
|---|---|---|---|---|---|
| 1.5 °C | 66% | 420 | 5.81 | 15.81 | 11.56 |
| | 50% | 580 | 8.48 | 22.29 | 16.42 |
| 1.75 °C | 66% | 800 | 12.16 | 31.20 | 23.10 |
| | 50% | 1040 | 16.17 | 40.92 | 30.39 |
| 2 °C | 66% | 1170 | 18.34 | 46.18 | 34.34 |
| | 50% | 1500 | 23.85 | 59.55 | 44.37 |

agreed on by the global community in the Paris Agreement (UNFCCC 2015). Therefore, having a significant chance of keeping the global mean temperature increase at 1.5 °C, even stricter and globally coordinated climate actions are needed.

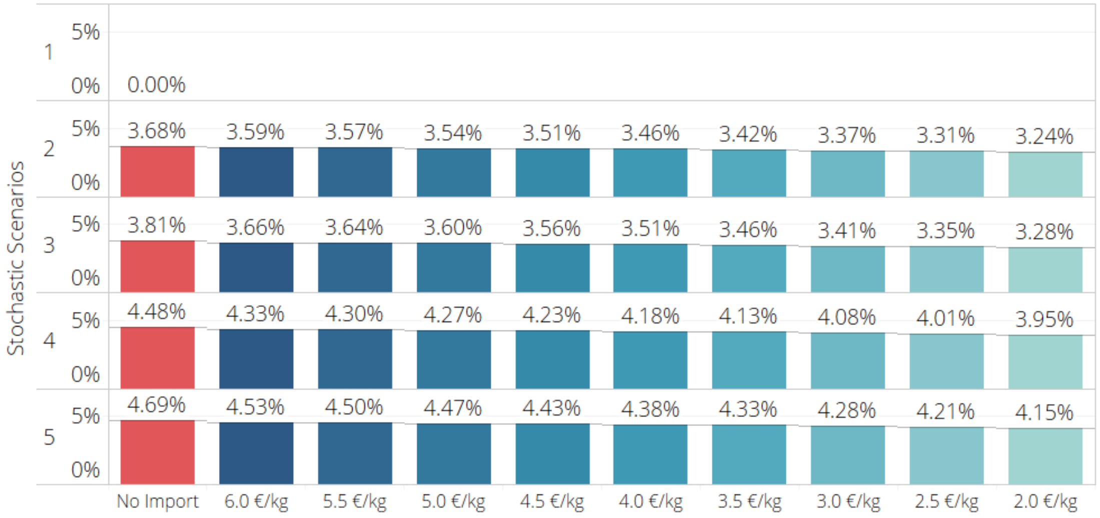

Figure 6.6: Increase of total system costs compared to the case with 1 stochastic scenario and no hydrogen imports. Own illustration.

In the case of 5 stochastic scenarios, hydrogen imports with 2.0 €/kg have a decreased objective value of 0.54% compared to not allowing hydrogen imports, as shown in Figure 6.6. Thus, although it shows that introducing hydrogen imports has a marginally positive effect on the overall system costs, the overall costs of planning an energy system without hydrogen are not much more costly than relying on large-scale hydrogen imports in the future. Nevertheless, hydrogen imports can still have an essential role in specific sectors of the energy system. However, the results also highlight that the cost increase for increased self-sufficiency is relatively insignificant from a whole system perspective.

### 6.4.2 Impact of uncertainty on long-term energy system planning

This sub-section explores the value a stochastic model can provide for long-term energy system planning. Starting with the total system costs in GENeSYS-MOD, it can be observed that introducing stochasticity increases the total system costs (compare Figure 6.6). Introducing only one additional stochastic scenario increases the total system costs by 3.7 %, whereas introducing further 4 stochastic scenarios (so, 5 in total) only increases the total system costs by an additional 1% (4.7 % from 1 to 5 stochastic scenarios).

For long-term planning of the power system, introducing stochasticity significantly affects capacity planning, as depicted by Figure 6.7. Without stochasticity and perfect foresight, much less renewable capacity is being invested in. However, with an increasing amount of stochastic scenarios, solar PV capacities are vastly increased (namely by 28% in the case with 5 stochastic scenarios compared to only 1 stochastic scenario). Also, the introduction of stochasticity has an additional incremental effect on power generation capacities utilizing hydrogen and energy storages in general, as more flexibility options are needed to cover the uncertainty of renewable electricity generation. The increased need for flexibility options and power generation capacities is the primary source of increased system costs in the cases with more stochastic scenarios.

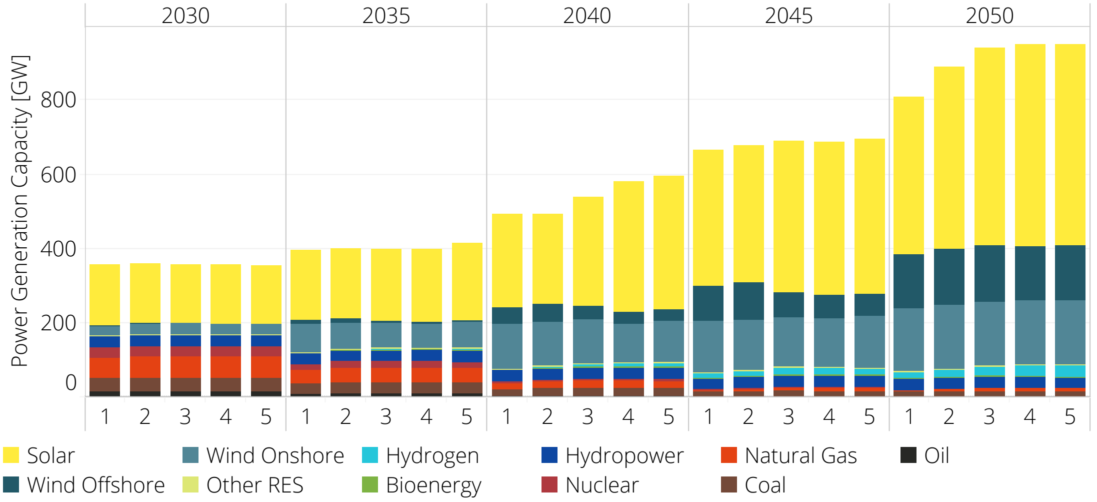

Figure 6.7: Power generation capacities in the case without hydrogen imports for the different stochastic scenarios in GENeSYS-MOD. Own illustration.

However, the impacts of stochasticity on long-term power system planning only play a role in cases without substantial conventional generation. In 2030, introducing stochasticity only has a limited effect on capacity planning, as uncertainty in renewable production can nearly always be met by ramping up conventional generators, and only from 2040 onward, substantial differences can be seen. The conventional generators still existing in 2050 in all scenarios are not being used by the model due to the constraint of having net-zero emissions and 2050 and no negative emission technologies available in this analysis. In this research, the existing conventional capacities in 2050 can not be run and end up stranded in the model. Nuclear power generation capacities are subsequently phased out until 2050, with only 5 GW of nuclear capacity still existing in 2040.

Overall, the differences in existing capacities also play a significant role in the operational planning of the actual power system dispatch. Using the capacities resulting from the model runs in GENeSYS-MOD, a power system dispatch model has been used to calculate the feasibility of the resulting power system. As seen in Figure 6.8, calculating a dispatch with the capacities planned while using only 1 stochastic scenario is only possible using *Infeasibility* power generation. Thus, it would not be possible to actually meet the power demand in that case in all hours. However, with 5 stochastic scenarios, the capacity planning is adequate to meet the demand for the whole year without using any *Infeasibility* power generation. Sensitivity analyses showed that this behavior could also be observed using various meteorological time-series as a data basis.[6]

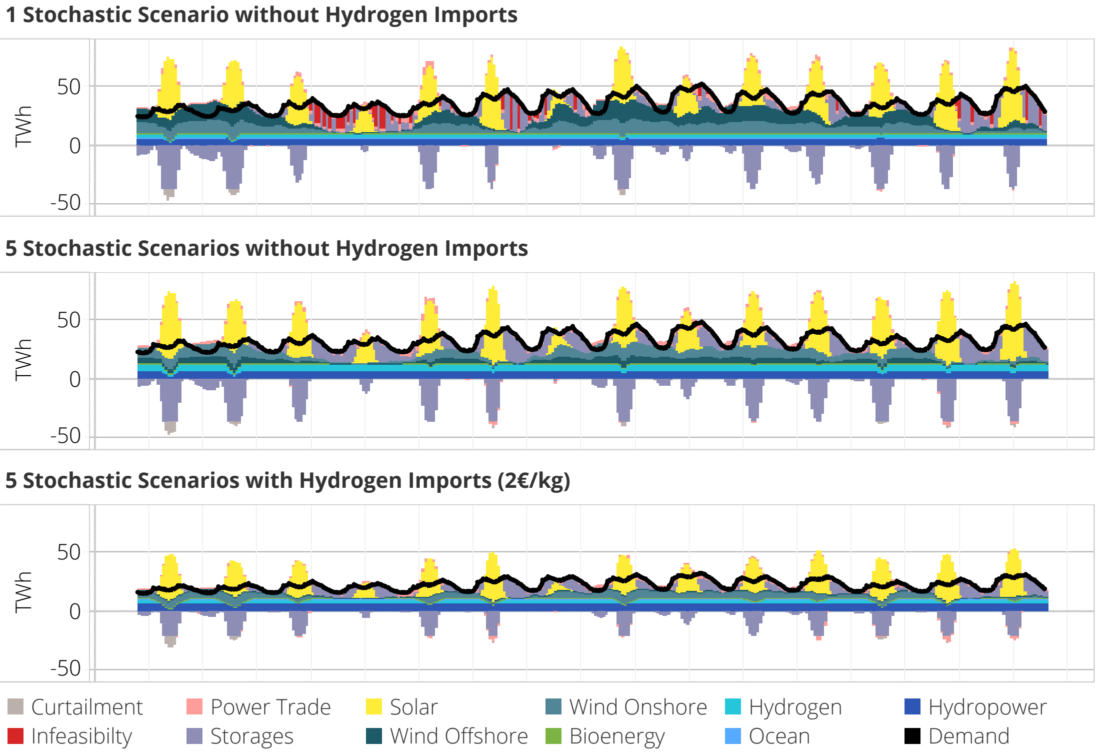

Figure 6.8: Power system dispatch for the 2nd and 3rd week of January in 2050 using renewable generation patterns from the meteorological year 2018. Own illustration.

Furthermore, it can be observed that with the increasing amount of stochastic scenarios, a cannibalizing effect of hydrogen and wind offshore can be observed. For the chosen

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[6] Figure 6.8 only shows a possible dispatch for the meteorological year 2018. However, the dispatch has been calculated and is feasible for different historical years when using 5 stochastic scenarios.

time frame in Figure 6.8, hydrogen needs to run as a base-load technology and storages providing peak-load flexibility or electricity when little wind or solar are available. Figure 6.7 shows that overall wind offshore and hydrogen capacities do not change substantially between the scenarios. However, the actual location and region where certain technologies are deployed changes with increasing amount of stochastic scenarios. It can be observed that hydrogen imports reduce the overall burden on the power system, as the overall power demand level is reduced, comparing the case with hydrogen import to the one without hydrogen imports. Hydrogen imports also result in less storage and flexibility capacity, as hydrogen and hydropower can produce a higher share of base-load power compared to the peak generation of renewables.

However, increasing the number of stochastic scenarios significantly increases the matrix size and computation time of GENeSYS-MOD. The actual matrix size increases nearly linearly from 100 GB (1 stochastic scenario) towards 410 GB (5 stochastic scenarios), the computation time increases exponentially. Consequently, a model run with 3 stochastic scenarios took 20 hours, 4 scenarios took 38 hours, and 5 scenarios took 120 hours of computation time. Due to the limit set by the utilized solving environment, a model run with 6 stochastic scenarios could not be run successfully in the available time frame.

### 6.4.3 Discussion of results and assumptions

Although this analysis provides sophisticated outlooks until 2050 for different cases with and without the possibility of hydrogen imports by using a stochastic large-scale open-source energy system model combined with a full-hourly power system dispatch model, several key limitations of the modeling approach exist. First of all, both utilized models belong to the class of linear optimization models. As such, critical features of macroeconomic models are missing. Hence, the model results are strongly dependent on exogenous assumptions such as GDP, population growth, or modal choice of transportation. For future analysis, coupling GENeSYS-MOD to a macroeconomic model can further enhance and validate the model results. Being a linear model, modeling decisions are often binary as soon as inherent prices reach certain thresholds. Furthermore, GENeSYS-MOD also acts as a system-optimizing social planner, neglecting competing interests of actions of firms, behaviors of individuals, and other participants of the energy transition.

Using stochastic scenarios compared to a full hourly time resolution for energy system planning poses advantages and disadvantages. Using a full-hourly resolution for all years might increase the feasibility of the power system development, as short-term variability and long-term intermittency are inherently included in the data. However, using the time-series of just one historical year bears a data bias for the future generation of renewable energy sources, especially in times of a constantly changing climate. Instead, using different historical years for producing stochastic scenarios adds a level of uncertainty for the future renewable generation that also increases the robustness of model results. Obviously, using different full-hourly time series as stochastic scenarios might further increase the feasibility of energy system and power system planning, with the downside of further increasing the computational complexity of the model.

Limited by computational resources, this analysis was carried out using aggregated regions of Japan instead of a detailed prefectural or nodal representation. However, a more detailed regional aggregation can indeed change the choice of technologies built or utilized, as shown by Burandt et al. (2019) and Oei et al. (2020). Therefore, future research should either increase the regional coverage of the energy system model or alternatively utilize an even more sophisticated power system dispatch model with preferably a non-convex representation of power transmission flows (e.g., using an optimal dc load flow model).

A further caveat of the modeling approach is the method of using constant hydrogen prices for different cases and unlimited capacities for hydrogen imports. In reality, prices are based on supply and demand and variable for given quantities of demand. However, this relationship cannot be expressed in a linear model, and, therefore, I opted for running several scenarios with different hydrogen import prices instead. The goal of this analysis was to look into the effects and implications resulting from large-scale hydrogen imports. For future analyses, coupling GENeSYS-MOD to a hydrogen market equilibrium model would undoubtedly lead to further insights.

As presented in this research article, substantial shares of renewable energies need to be deployed in Japan for reaching ambitious climate targets. With Japan being an insular state with limited land availability, the actual amounts of usable area for solar PV and wind can be discussed. In this study, most of the available potentials for variable renewable energy sources have been utilized in the case without hydrogen imports. Still, the potentials have been calculated using today's efficiencies and land utilization rates and thus, higher potentials might be assumed for the future. Also, Esteban et al. (2018) conclude similar capacities and production levels of renewable energies in their study. They also do not consider hydrogen imports and furthermore only assess the power sector. In contrast, in the results presented in this study an integrated approach to modeling sector-coupling effects is included and thus, even higher demand levels for electricity can be observed. Similarly, in other studies of the Japanese energy system (Sugiyama et al. 2019; Kato and Kurosawa 2019; Fujimori et al. 2019) only 80% emission reduction scenarios have been analyzed, naturally resulting in much less power generation from renewable energy sources. Furthermore, in studies focusing 80% emission reduction targets, less electrification and sector-coupling technologies have to be deployed, resulting in less overall power demand.

All in all, I want to stress that the results of this analysis should not be considered foresight in a traditional sense. In general, numerical models should only be used to generate insights and not exact numbers for future predictions (Huntington, Weyant, and Sweeney 1982). Nevertheless, this analysis still provides novel and valuable insights about both the role of hydrogen imports in a multi-sectoral energy system model, especially for the case of Japan, as well as the impact of stochasticity on long-term energy system planning. However, this paper only looks at the time frame until 2050, as the Japanese Prime-Minster set this date for reaching net-zero emissions. Therefore, it could also be beneficial to look into long-term energy system analyses for the years after 2050 in future research work.

## 6.5 Recommendations

Overall, this research highlights that the ambitious target of net-zero emissions in 2050, which the Japanese Prime-Minister has announced, can generally be achieved. These findings are relevant for Japan and other countries and regions aiming at net-zero emissions, such as e.g., the USA, the European Union, China, Germany. Complying with these ambitious goals of net-zero emissions by the mid of the century is required to keep global warming below 1.5°C (Climate Action Tracker 2020). In this regard, this research also explored the decarbonization of all sectors of the energy system without the deployment of carbon capture and storage and nuclear energy. Even without hydrogen imports, such decarbonization seems possible, even though immediate and large-scale deployment of additional renewable energy sources together with short-term and long-term energy storages would be needed. To prevent large-scale lock-in effects and to achieve ambitious climate goals, investments in fossil fuels need to be reduced as soon as possible. This again is not only true for Japan, but also for other regions that are currently relying on large shares of fossil fuels as their primary energy sources (e.g., China, Germany, USA, compare Burandt et al. (2019), Bartholdsen et al. (2019), and Zozmann et al. (2021)).

For reaching net-zero emissions, the hydrogenification of industrial sectors and the transportation sector is often deemed key. Not only for Japan but also for Germany, importing substantial amounts of hydrogen is presented as necessary in some studies (Prognos, Öko-Institut, and Wuppertal-Institut 2020). In general, hydrogen poses a valuable resource in specific sectors of the energy system, and importing hydrogen can positively impact energy system developments. Still, policy- and decision-makers should move away from portraying hydrogen as the one and only savior for the energy system and instead focus on the large-scale deployment of readily available and cost-efficient variable renewable power generation technologies to reach ambitious decarbonization targets. Regarding infrastructure investments, hydrogen is often used as an excuse by incumbent actors to keep existing gas infrastructure alive by promising a switch to hydrogen at a later stage. However, unnecessary additional investments into natural-gas-based infrastructure might create unwanted path dependencies and lock-in effects. Hence, it needs to be ensured that the fuel switch from natural gas to hydrogen can realistically happen without the need for additional retrofitting costs (Van de Graaf et al. 2020; Brauers, Braunger, and Jewell 2021).

In contrast, in sector-coupled energy systems, the power sector will always play a crucial role as it will provide energy either for direct use in non-electricity sectors or for the generation of hydrogen and synthetic fuels. Only cheap and broadly available renewable energy sources provide the basis for cost-efficient hydrogen production and electrification of the heat, transport, and industrial sectors. Especially in light of the radical steps needed for decarbonization of all sectors, ambitious actions in the power system are needed.

Lastly, the decarbonization of the energy system is relevant not only for Japan but for the whole global community. Decarbonization of the energy system requires a global context, but regional solutions, as climate change is a global issue but relevant on local scales. Thus policy- and decision-makers should aim for further international coordination. Furthermore, importing hydrogen from countries producing it either via fossil power or via steam methane reforming technologies (without CCS) alleviates the ambitions to fight climate change. The goal for policy- and decision-makers should be to plan global hydrogen markets solely focused on green or blue hydrogen.[7]

## 6.6 Conclusions

This analysis explored the impact of the availability of hydrogen imports and their effects on the development of the Japanese energy system. With the combination of a stochastic energy system model and a power system dispatch model, technological developments in specific sectors resulting from the possibility of hydrogen imports have been explored. Furthermore, the value of using a stochastic energy system model for long-term energy system planning has been presented in the research. Key results include that hydrogen can indeed play a significant role in the industry sector if enough cheap hydrogen can be imported. However, even in the case with the cheapest hydrogen import prices (2 €/kg), renewable energy sources still provide the largest share of the Japanese primary energy consumption. Thus, the Japanese energy system will never transition towards a full ”Hydrogen Society”, where hydrogen provides the primary energy carrier in most of the sectors

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[7] Green hydrogen represents hydrogen produced from renewable energies via electrolysis and blue hydrogen represents hydrogen produced via steam methane reforming with CCS.

of an energy system. Instead, utilizing domestic renewable energy sources and electrification of most sectors prove the most cost-efficient way of decarbonizing the energy system. Without hydrogen imports, the deep decarbonization of the energy system results in significant electrification means in most of the sectors, and thus, the overall power demand of the Japanese energy system will almost double compared to 2019 levels. Furthermore, based on modeling results, hydrogen will always play just an ancillary role in the power system, as most of the domestic and imported hydrogen is more valuable to be used in other sectors. However, fuel cells and combined heat and power plants pose a cost-efficient way of producing electricity and heat for commercial and residential buildings and provide cycling and ramping capabilities for the power system.

Secondly, this research also highlights that using stochasticity in large-scale multi-sectoral energy system models can result in more robust results, especially regarding power system developments. Using stochasticity and uncertainty is advantageous for power system planning, as variable renewable energy sources have an uncertain power generation pattern in reality. Coupling a multi-sectoral energy system model with a dedicated power system dispatch model allows for a further assessment of the feasibility of the resulting power system.

# Part III

# APPENDICES

## Appendix A

# Appendix to Chapter 1: Introduction

Table A.1: Further publications with GENeSYS-MOD

| Year | Publication |
|---|---|
| 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 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. |
| 2020 | T. Burandt, P. Crespo del Granado, and R. Egging-Bratseth. 2020. „Stranded Assets, and the Role of Biomass and Hydrogen in the European Energy Transition.“ *IAEE Energy Forum,* Energy Forum, 2020 (Q1): 33–36. |
| 2019 | L. Sarmiento et al. 2019. „Analyzing Scenarios for the Integration of Renewable Energy Sources in the Mexican Energy System—An Application of the Global Energy System Model (GENeSYS-MOD).“ *Energies* 12 (17): 3270. https://doi.org/10.3390/en12173270. |
| 2019 | H.-K. Bartholdsen et al. 2019. „Pathways for Germany's Low-Carbon Energy Transformation Towards 2050.“ *Energies* 12 (15): 2988. https://doi.org/10.3390/en12152988. |
| 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 | L. Lawrenz et al. 2018. „Exploring Energy Pathways for the Low-Carbon Transformation in India—A Model-Based Analysis.“ *Energies* 11 (11): 3001. https://doi.org/10.3390/en11113001. |

| | |
|---|---|
| 2018 | T. Burandt, K. Löffler, and K. Hainsch. 2018. „GENeSYS-MOD v2.0 - Enhancing the Global Energy System Model.“ *DIW Data Documentation* 94. |
| 2018 | F. Gardumi et al. 2018. „From the development of an open-source energy modelling tool to its application and the creation of communities of practice: The example of OSeMOSYS.“ *Energy Strategy Reviews* 20:209–228. https://doi.org/10.1016/j.esr.2018.03.005. |
| 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, 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. |

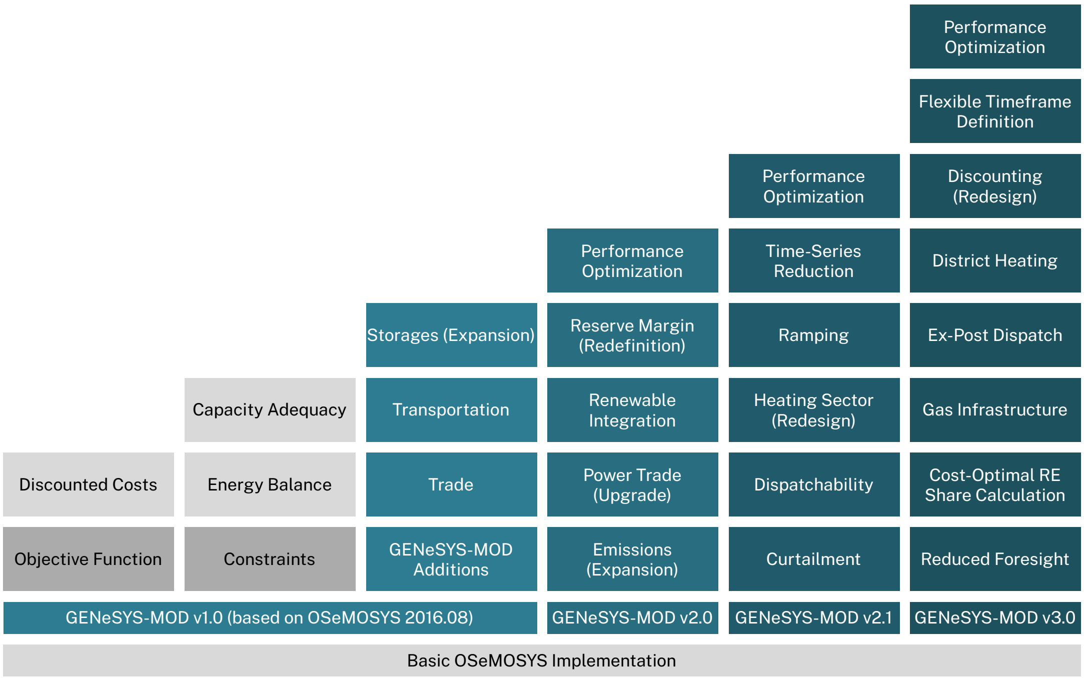

Figure A.1: GENeSYS-MOD versions and model additions

## Appendix B

# Appendix to Chapter 2: Designing a model for the Global energy system – GENeSYS-MOD

## B.1 List of sets and parameters

| Set Name (Abbreviation) | Set Description |
|---|---|
| Daylytimebracket (lh) | Allows for day/night differentiation, i.e., splits a single day into brackets |
| Daytype (ld) | Allows to model different days like weekday/weekend |
| Emissions (e) | Emissions produced by the different technologies |
| *Fuel (f)* | Fuels enter or leave technologies. Demands are always for specific fuels. |
| Modaltype (mt) | Allows for the modal split in the transportation sector. |
| Mode of Operation (m) | Technologies might operate in different modes, enabling different input-output combinations |
| *Region (r)* | The different (aggregated) regions considered. |
| Season (ls) | Allows a differentiation for yearly seasons (e.g., summer/winter). |
| Storage (s) | The set of different storage technologies. |
| *Technology (t)* | Everything that processes energy in any form is considered a technology. |
| Timeslice (l) | Timeslices are a combination of ls, ld, and lh. Hence, one timeslice could be "summer weekend day" . |
| *Year (y)* | The set of the different modeled years. |

| Parameter Name | Parameter Description |
|---|---|
| $AccumulatedAnnualDemand_{f,r,y}$ | Amount of demand that can be satisfied at any time of the year, not time-slice dependent. |
| $AnnualEmissionLimit_{e,r,y}$ | Amount of emissions allowed in a year and region. |
| $AnnualExogenousEmission_{e,r,y}$ | Amount of emissions not produced by modeled technologies in a given year. |
| $AvailabilityFactor_{r,t,y}$ | Maximum time a technology may run in a year. |
| $CapacityFactor_{l,t,r,y}$ | Maximum time a technology may run in a time-slice. |
| $CapacityToActivityUnit_{r,t}$ | Conversion factor of capacities [GW] into activity [PJ]. Assumes provision of 1 [GW] over one year. |
| $CapitalCostStorage_{r,s,y}$ | Capital costs for storage technologies. |
| $CapitalCost_{r,t,y}$ | Capital cost for all technologies. |
| $Conversionlh_{l,lh}$ | Assigns DailyTimeBracket to time-slice. |
| $Conversionld_{l,ld}$ | Assigns DayType to time-slice. |
| $Conversionls_{l,ls}$ | Assigns Season to time-slice. |

| | |
|---|---|
| $DaySplitl_{h,y}$ | Length of a DailyTimeBracket in one day as a fraction of the year. |
| $DaysInDayType_{ld,ls,y}$ | Amount of days per week in which a DayType occurs. |
| $EmissionsActivityRatio_{e,m,r,t,y}$ | Amount of emissions produced by a technology for producing 1 [PJ] of energy. |
| $EmissionsPenalty_{e,r,y}$ | Penalty for emitting emissions. |
| $FixedCost_{r,t,y}$ | Fixed O&M costs for a technology. |
| $InputActivityRatio_{f,m,r,t,y}$ | Describes coupled with OutputActivityRatio the efficiency of a technology. |
| $MinStorageCharge_{r,s,y}$ | Percentage of storage capacity that must not be deceeded. |
| $ModalSplitByFuelAndModalType_{f,mt,r,y}$ | Assigns the share of a mean of transportation for one demand fuel. |
| $ModelPeriodEmissionLimit_{e,r}$ | Amount of emissions that must not be exceeded over the whole modeling period. |
| $ModelPeriodExogenousEmission_{e,r}$ | Amount of emissions that is not produced by a modeled technology in whole modeling period. |
| $OperationalLifeStorage_{r,s,y}$ | Operational life of storage technologies. |
| $OperationalLife_{r,t}$ | Operational life of all technologies. |
| $OutputActivityRatio_{f,m,r,t,y}$ | Describes coupled with InputActivityRatio the efficiency of a technology. |
| $RETagFuel_{f,r,y}$ | Tags fuels that do not produce emissions. |
| $RETagTechnology_{r,t,y}$ | Tags technologies that do not produce emissions. |
| $ReserveMarginTagFuel_{f,r,y}$ | Tags whether more than the actual demand has to be produced of a given fuel. |
| $ReserveMarginTagTechnology_{r,t,y}$ | Tags which technologies can contribute to the reserve margin. |
| $ReserveMargin_{r,y}$ | Sets the amount of reserve margin that has to be produced. |
| $ResidualCapacity_{r,t,y}$ | Capacities that exist in addition to the endogenously built capacities. |
| $ResidualStorageCapacity_{r,s,y}$ | Storage Capacities that exist in addition to the endogenously built capacities. |
| $SpecifiedAnnualDemand_{f,r,y}$ | Annual demand of fuels which are time-slice dependent. |

| | |
|---|---|
| *SpecifiedDemandProfile*$_{f,r,t,y}$ | Assigns a share of SpecifiedAnnualDemand to the different time-slices. |
| *StorageLevelStart*$_{r,s}$ | Amount of stored energy at the beginning of the modeling period. |
| *StorageMaxChargeRate*$_{r,s}$ | Maximum charge amount of a storage within one hour |
| *StorageMaxDischargeRate*$_{r,s}$ | Maximum discharge amount of a storage within one hour |
| *TagTechnologyToModalType*$_{mt,t}$ | Assigns different transportation technologies to the modal type. |
| *TechnologyFromStorage*$_{m,r,s,t}$ | Technologies that can use a fuel from a storage. |
| *TechnologyToStorage*$_{m,r,s,t}$ | Technologies that can provide a fuel for a storage. |
| *TotalAnnualMaxCapacityInvestment*$_{r,t,y}$ | Maximum amount of investments into a technology in a year. |
| *TotalAnnualMaxCapacity*$_{r,t,y}$ | Maximum amount of used capacity in a year. |
| *TotalAnnualMinCapacityInvestment*$_{r,t,y}$ | Minimum amount of investments into a technology in a year. |
| *TotalAnnualMinCapacity*$_{r,t,y}$ | Minimum amount of used capacity in a year. |
| *TradeCosts*$_{f,r,rr}$ | Variable costs for trading a fuel between regions. |
| *TradeRoutes*$_{f,r,rr,y}$ | Tags possible trade routes between regions. |
| *VariableCost*$_{m,r,t,y}$ | Variable O&M costs for using a technology. |
| *YearSplit*$_{l,y}$ | Share of a time-slice in one year. |

## B.2 List of technologies and storages

| **Technology** | **Parameter Description** |
|---|---|
| Area_DistrictHeating_avg | Usable area for centralized heating (average) |
| Area_DistrictHeating_inf | Usable area for centralized heating (inferior) |
| Area_DistrictHeating_opt | Usable area for centralized heating (optimal) |
| Area_PV_Commercial | Usable area for commercial rooftop PV systems |
| Area_Solar_Roof | Usable area for private rooftop PV systems |
| BIOFLREFINERY | Refinery for biomass to biofuel conversion |
| C_Coal | Coal resource node |
| C_Gas | Gas resource node |
| C_Nuclear | Nuclear material resource node |
| C_Oil | Crude oil resource node |

| | |
|---|---|
| ELYSER | Hydrogen-producing elyser |
| FRT_Rail_ELC | Freight rail transport; Electric train |
| FRT_Rail_Petro | Freight rail transport; Petro-fueled |
| FRT_Road_Bio | Freight road transport; Biofuels |
| FRT_Road_Conv | Freight road transport; Conventional fuels |
| FRT_Road_H2 | Freight road transport; Hydrogen-based |
| FRT_Ship_Bio | Freight ship transport; Biofuels |
| FRT_Ship_Conv | Freight ship transport; Conventional fuels |
| FUEL_CELL | Fuel cell |
| H2TL | Hydrogen liquefaction |
| P_Coal | Coal-based power plant |
| P_Gas | Natural gas-based power plant |
| P_Nuclear | Nuclear power plant |
| P_Oil | Oil power plant |
| PSNG_Air_Conv | Passenger air transport; Conventional fuels |
| PSNG_Air_H2L | Passenger air transport; Liquid hydrogen |
| PSNG_Rail_ELC | Passenger rail transport; Electric train |
| PSNG_Rail_Petro | Passenger rail transport; Petro-fueled |
| PSNG_Road_BEV | Passenger road transport; Battery electric vehicle |
| PSNG_Road_Bio | Passenger road transport; Biofuels |
| PSNG_Road_FCEV | Passenger road transport; Fuel cell electric vehicle |
| PSNG_Road_ICE | Passenger road transport; Internal combustion engine |
| Res_Biomass | Biomass resource node |
| Res_CSP | Concentrated solar power plant |
| Res_CSP_Storage | Concentrated solar power plant with integrated storage |
| Res_Hydro_Large | Large-scale hydro (>25MW) |
| Res_Hydro_Small | Small-scale hydro |
| Res_PV_Commercial | Rooftop-PV on commercial buildings |
| Res_PV_Residential | Residential rooftop PV systems |
| Res_PV_Utility_avg | Utility-scale PV (average) |
| Res_PV_Utility_inf | Utility-scale PV (inferior) |
| Res_PV_Utility_opt | Utility-scale PV (optimal) |
| Res_Thermal_Geo | Geothermal power generation |
| Res_Thermal_Solar | Solar-based heat generation |
| Res_Tidal | Tidal power plant |
| Res_Wave | Wave power plant |
| Res_Wind_Offshore_avg | Offshore wind plant (average) |

| | |
|---|---|
| Res_Wind_Offshore_inf | Offshore wind plant (inferior) |
| Res_Wind_Offshore_opt | Offshore wind plant (optimal) |
| Res_Wind_Onshore_avg | Onshore wind plant (average) |
| Res_Wind_Onshore_inf | Onshore wind plant (inferior) |
| Res_Wind_Onshore_opt | Onshore wind plant (optimal) |
| ST_Battery_Lion | Dummy-Technology for battery storage |
| ST_H2 | Dummy-Technology for hydrogen storage |
| ST_Heat_cen | Dummy-Technology for central heat storage |
| ST_Heat_dec | Dummy-Technology for decentral heat storage |
| ST_PSP | Dummy-Technology for pump storage |
| ST_PSP_Residual | Dummy-Technology for residual pump storage capacities |
| T_heat_high_bio | High-temperature heat generation (biomass) |
| T_heat_high_coal | High-temperature heat generation (coal) |
| T_heat_high_elfur | High-temperature heat generation (electric furnace) |
| T_heat_high_gas | High-temperature heat generation (natural gas) |
| T_heat_high_oil | High-temperature heat generation (oil) |
| T_heat_high_res-gas | High-temperature heat generation (hydrogen) |
| T_heat_low_bio | Low-temperature heat generation (biomass) |
| T_heat_low_bio_cen | Low-temperature heat generation (biomass; centralized) |
| T_heat_low_bio_chp | Low-temperature heat generation (biomass; combined heat-power-plant) |
| T_heat_low_bio_chp_cen | Low-temperature heat generation (biomass; centralized; combined heat-power-plant) |
| T_heat_low_coal | Low-temperature heat generation (coal) |
| T_heat_low_coal_cen | Low-temperature heat generation (coal; centralized) |
| T_heat_low_coal_chp_cen | Low-temperature heat generation (coal; centralized; combined heat-power-plant) |
| T_heat_low_elfur | Low-temperature heat generation (electric furnace) |
| T_heat_low_elfur_cen | Low-temperature heat generation (electric furnace; centralized) |
| T_heat_low_gas | Low-temperature heat generation (natural gas) |
| T_heat_low_gas_cen | Low-temperature heat generation (natural gas; centralized) |
| T_heat_low_gas_chp_cen | Low-temperature heat generation (natural gas; centralized; combined heat-power-plant) |
| T_heat_low_heatpump | Low-temperature heat generation (heatpump) |
| T_heat_low_heatpump_cen | Low-temperature heat generation (heatpump; centralized) |

| | |
|---|---|
| T_heat_low_oil | Low-temperature heat generation (oil) |
| T_heat_low_oil_cen | Low-temperature heat generation (oil; centralized) |
| T_heat_low_oil_chp_cen | Low-temperature heat generation (oil; centralized; combined heat-power-plant) |
| T_heat_low_res-gas | Low-temperature heat generation (hydrogen) |
| T_heat_low_res-gas_cen | Low-temperature heat generation (hydrogen; centralized) |
| T_heat_low_res-gas_chp | Low-temperature heat generation (hydrogen; combined-heat-power-plant) |
| T_heat_low_res-gas_chp_cen | Low-temperature heat generation (hydrogen; centralized; combined heat-power-plant) |
| Storages | |
| S_Battery_Lion | Lithium-Ion battery |
| S_CSP_storage | Storage-technology connected to CSP with storage |
| S_H2 | Hydrogen (gas) storage |
| S_Heat_cen | Heat storage for central heating |
| S_Heat_dec | Heat storage for decentral heating |
| S_PSP | (Hydro) Pump-storage-plant |

## B.3 List of countries, grouped by region

**Africa**

- Algeria
- Angola
- Benin
- Botswana
- Burkina Faso
- Burundi
- Cabo Verde
- Cameroon
- Central African Republic
- Chad
- Comoros
- Congo
- Côte D'Ivoire
- Congo
- Djibouti
- Egypt
- Equatorial Guinea
- Eritrea
- Ethiopia
- Gabon
- Gambia (Islamic Republic of)
- Ghana
- Guinea
- Guinea Bissau
- Kenya
- Lesotho
- Liberia
- Libya
- Madagascar
- Malawi
- Mali
- Mauritania
- Mauritius
- Morocco
- Mozambique
- Namibia
- Niger
- Nigeria
- Rwanda
- Sao Tome and Principe
- Senegal
- Sierra Leone
- Somalia
- South Africa
- South Sudan
- Sudan
- Swaziland
- Togo
- Tunisia
- Uganda
- United Republic of Tanzania
- Zambia
- Zimbabwe

**Asia-Rest**

- Bangladesh
- Bhutan
- Brunei Darussalam
- Cambodia
- Indonesia
- Laos
- Malaysia
- Maldives
- Myanmar
- Nepal
- Philippines
- Seychelles
- Singapore
- Sri Lanka
- Thailand
- Timor-Leste
- Vietnam

**China**

- China
- Mongolia

**Europe**

- Albania
- Andorra
- Austria
- Belarus
- Belgium
- Bosnia and Herzegovina
- Bulgaria
- Croatia
- Cyprus
- Czech Republic
- Denmark
- Estonia
- Finland
- France
- Germany
- Greece
- Hungary
- Iceland
- Ireland
- Italy
- Latvia
- Liechtenstein
- Lithuania
- Luxembourg
- Malta
- Monaco
- Montenegro
- Netherlands
- Norway
- Poland
- Portugal
- Romania
- San Marino
- Serbia
- Slovakia
- Slovenia
- Spain
- Sweden
- Switzerland
- Macedonia
- Ukraine
- United Kingdom

**India**

- India

**Middle East**

- Afghanistan
- Bahrain
- Iran (Islamic Republic of)
- Iraq
- Israel
- Jordan
- Kuwait
- Lebanon
- Oman
- Pakistan
- Qatar
- Saudi Arabia
- Syrian Arab Republic
- Turkey
- United Arab Emirates
- Yemen

**North America**

- Canada
- Mexico
- USA

**Ocenania**

- Australia
- North Korea
- Fiji
- Japan
- Kiribati
- Marshall Islands
- Micronesia
- Nauru
- New Zealand
- Palau
- Papua New Guinea
- South Korea
- Samoa
- Solomon Islands
- Tonga
- Tuvalu
- Vanuatu

**FSU**

Armenia
Azerbaijan
Georgia
Kazakhstan
Kyrgyzstan
Russian Federation
Tajikistan
Turkmenistan
Uzbekistan
Republic of Moldova

**South America**

Antigua and Barbuda
Argentina
Bahamas
Barbados
Belize
Bolivia
Brazil
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Grenada
Guatemala
Guyana
Haiti
Honduras
Jamaica
Nicaragua
Panama
Paraguay
Peru
Saint Kitts and Nevis
Saint Lucia
Saint Vincent and the Grenadines
Suriname
Trinidad and Tobago
Uruguay
Venezuela

## B.4 Capital cost development of electricity-generating technologies

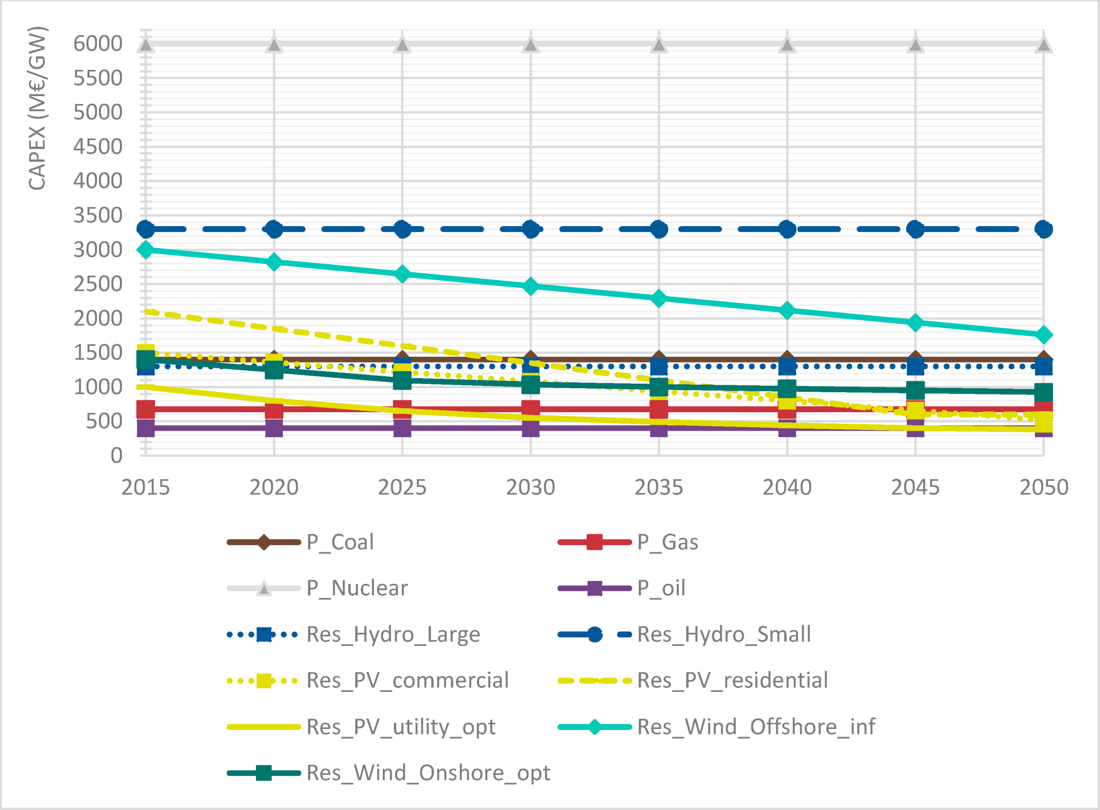

Figure B.1: Capital Cost development of power-generating technologies.

## Appendix C

# Appendix to Chapter 4: Modeling the low-carbon transition of the European energy system

## 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. 2011.

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).

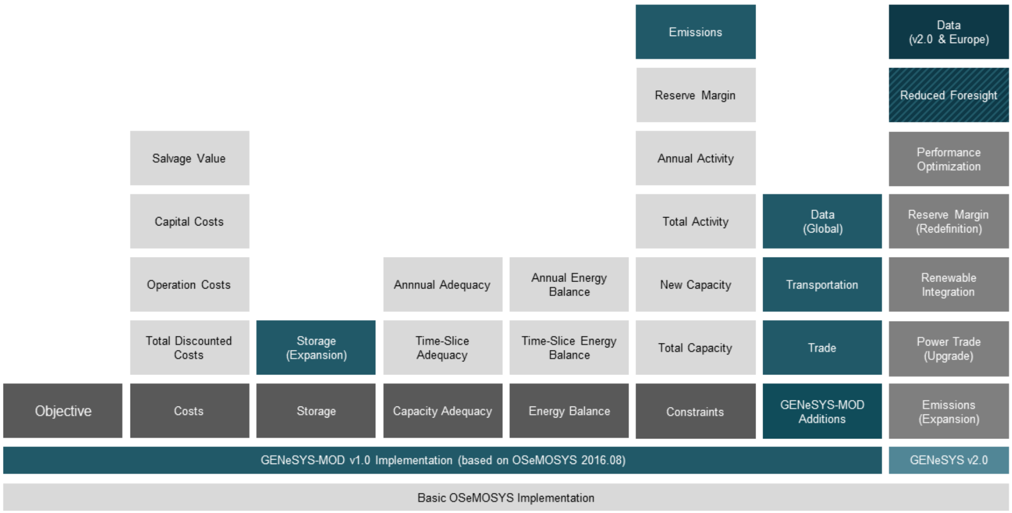

Figure C.1: Model structure of the GENeSYS-MOD implementation used in this study. Source: Own illustration.

(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. 2011; Löffler, Hainsch, Burandt, Oei, Kemfert, et al. 2017; Burandt, Löffler, and Hainsch 2018.

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[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

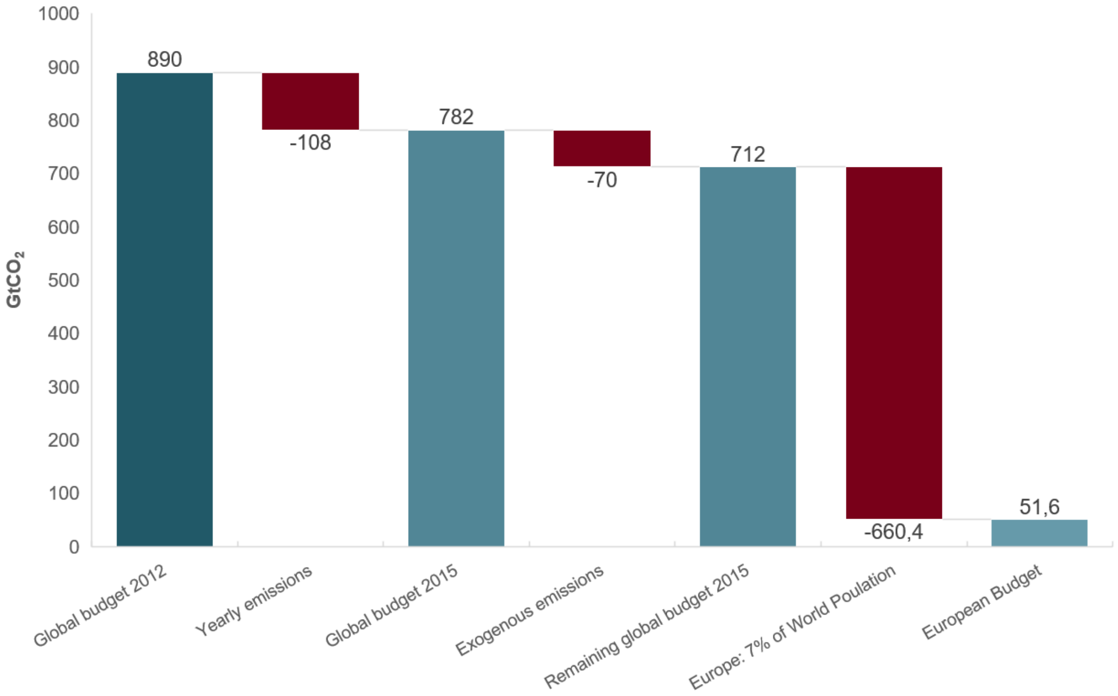

Figure C.2: Emission budget calculations. Source: Own illustration.

## 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).

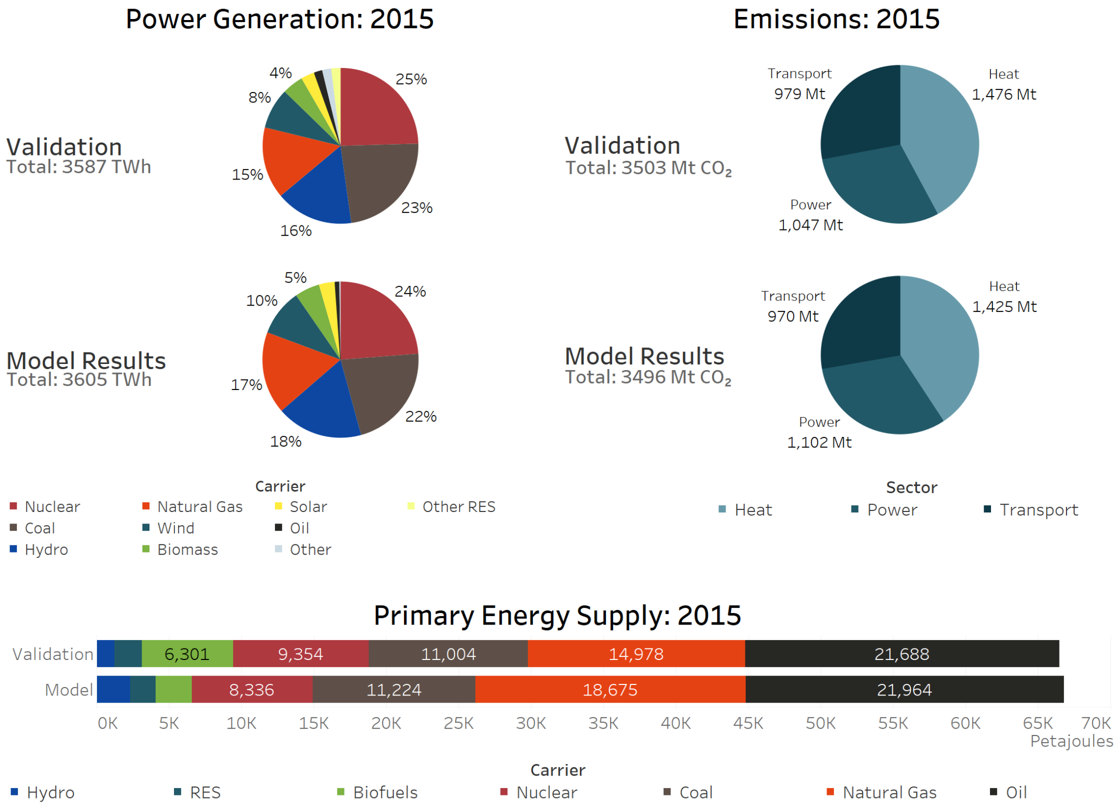

Figure C.3: Comparison of 2015 model results vs. historical numbers. Source: Own calculations, 2015 data based on International Energy Agency 2018a; Statistical Office of the Republic of Serbia 2017; Statistics Norway 2017; Swissgrid 2015; International Energy Agency 2018b; OECD 2017.

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 |

Source: Gerbaulet and Lorenz (2017a).

The solar PV potentials taken from Gerbaulet and Lorenz (2017a) are exhausted in some regions as soon as 2030 in the BASE scenario. This appears to be relatively early, as compared to other studies in the literature (compare, for example, (Ram et al. 2017)). Therefore, an assessment of solar potentials has been conducted as a sensitivity analysis, using solar irradiation data and assuming a usable amount of land of 4% across all regions. The results show that the possible solar potential heavily influences the results for a transition towards renewables in Europe. Especially in southern Europe, higher amounts of solar capacities are constructed and shift both the resulting production mix and the grid structure and expansion. For a detailed presentation of these sensitivity runs, please refer to Hainsch et al. (2021).

**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 |

Source: Carlsson et al. (2014), Gerbaulet and Lorenz (2017a), 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 |

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% |

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 |

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 |

Source: Gerbaulet and Lorenz (2017a).

## Appendix D

# Appendix to Chapter 5: Decarbonizing China’s energy system

## D.1 Data

This section presents some additional key data for the analysis. More supplementary data is provided in the *Mendeley Data* repository provided by Burandt (2019).

**Technology Costs**

| | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Utility PV | 1020 | 790 | 695 | 600 | 525 | 450 | 410 | 370 |
| Onshore Wind | 1250 | 1150 | 1060 | 1000 | 965 | 940 | 915 | 900 |
| Offshore Wind | 3500 | 2637 | 2200 | 1936 | 1800 | 1710 | 1642 | 1592 |
| Geothermal | 5250 | 4970 | 4720 | 4470 | 4245 | 4020 | 3815 | 3610 |
| Biomass Thermal Plant | 2890 | 2620 | 2495 | 2370 | 2260 | 2150 | 2050 | 1950 |
| Hydropower (Large-Scale) | 2200 | 2200 | 2200 | 2200 | 2200 | 2200 | 2200 | 2200 |
| Hydropower (Small-Scale) | 4400 | 4480 | 4490 | 4500 | 4500 | 4500 | 4500 | 4500 |
| Coal-Fired Thermal Plant | 1600 | 1600 | 1600 | 1600 | 1600 | 1600 | 1600 | 1600 |
| Gas-Fired Thermal Plant | 650 | 636 | 621 | 607 | 593 | 579 | 564 | 550 |
| Oil-Fired Thermal Plant | 650 | 627 | 604 | 581 | 559 | 536 | 513 | 490 |
| Coal-Fired CHP | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 | 2030 |
| Gas-Fired CHP | 977 | 955 | 934 | 912 | 891 | 869 | 848 | 826 |
| Oil-Fired CHP | 819 | 790 | 761 | 733 | 704 | 675 | 646 | 617 |

Table D.1: Capital costs of main electricity generating technologies in M€/GW. Data based on Carlsson et al. (2014), Gerbaulet and Lorenz (2017a), Ram et al. (2019), and Burandt, Löffler, and Hainsch (2018).

**Ramping Parameters**

| | Ramping Up | Ramping Down | Ramping Costs in €/MWh |
|---|---|---|---|
| Hydropower (Large-scale) | 25% | 25% | 50 |
| Biomass Power Plant | 4% | 4% | 50 |
| Nuclear Power Plant | 1% | 1% | 200 |
| Coal-Fired Thermal Plant | 4% | 4% | 50 |
| Gas-Fired Thermal Plant | 20% | 20% | 20 |
| Oil-Fired Thermal Plant | 6% | 6% | 50 |

Table D.2: Capital costs of main electricity generating technologies in M€/GW. Data based on Carlsson et al. (2014) and Gerbaulet and Lorenz (2017a).

### Fuel Costs

| | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Oil [Import] | 7.12 | 10.18 | 11.02 | 11.86 | 11.37 | 10.88 | 8.99 | 7.11 |
| Coal [Import] | 4.50 | 4.57 | 4.54 | 4.50 | 4.35 | 4.19 | 4.07 | 3.94 |
| Nat. Gas [Import] | 8.81 | 8.15 | 9.00 | 9.86 | 9.90 | 9.95 | 10.00 | 10.05 |
| Coal [Inner Mongolia] | 0.81 | 0.82 | 0.82 | 0.82 | 0.78 | 0.75 | 0.73 | 0.71 |
| Coal [Shaanxi] | 1.54 | 1.56 | 1.55 | 1.54 | 1.49 | 1.43 | 1.39 | 1.35 |
| Coal [Ningxia] | 1.58 | 1.60 | 1.59 | 1.58 | 1.52 | 1.47 | 1.43 | 1.38 |
| Coal [Guizhou] | 3.60 | 3.65 | 3.62 | 3.60 | 3.47 | 3.35 | 3.25 | 3.15 |

Table D.3: Import fossil fuel cost in M€/PJ and domestic costs of hard-coal in primary coal-exporting provinces, based on International Energy Agency (2017) and He et al. (2016).

### Demand

| | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Power [PJ] | 9858 | 10775 | 11590 | 12404 | 12753 | 13101 | 13264 | 13426 |
| Industry (High) [PJ] | 23061 | 24342 | 25374 | 26406 | 26620 | 26833 | 27211 | 27588 |
| Industry (Medium) [PJ] | 12890 | 13607 | 14183 | 14760 | 14880 | 14999 | 15210 | 15421 |
| Industry (Low) [PJ] | 5307 | 5602 | 5840 | 6077 | 6126 | 6175 | 6262 | 6349 |
| Buildings [PJ] | 12096 | 12952 | 13794 | 14637 | 15341 | 16045 | 17717 | 18510 |
| Freight-Mobility [gtkm] | 15667 | 19699 | 23716 | 27704 | 31636 | 35324 | 38288 | 39643 |
| Passenger-Mobility [gpkm] | 2838 | 3360 | 3930 | 4499 | 4684 | 4870 | 4918 | 4967 |

Table D.4: Sector-specific demands, based on International Energy Agency (2017) and National Energy Administration (NEA) China (2019).

### Renewable capacity factors

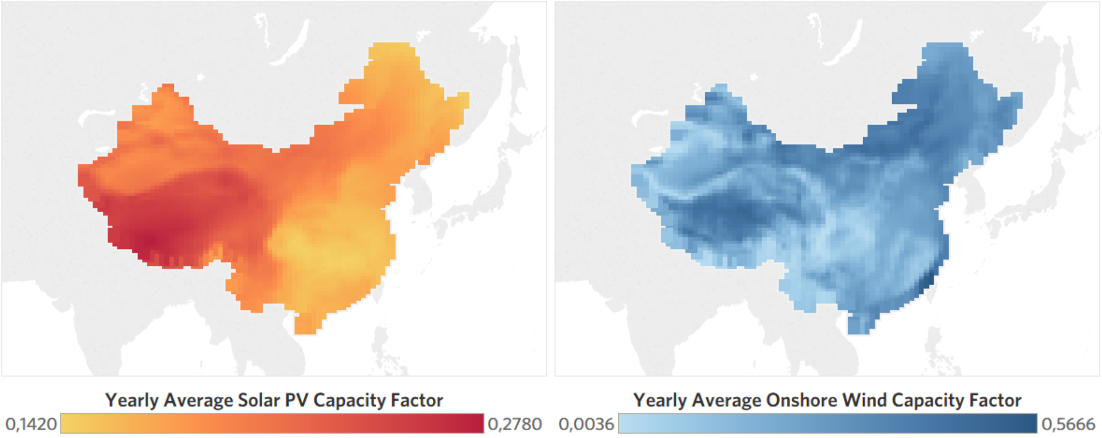

Figure D.1: Presentation of the yearly average capacity factors for onshore wind and solar PV per data point in a 50x50km grid. Source: Own illustration.

## D.2 GENeSYS-MOD: blocks of functionality

This section shortly describes the main components of GENeSYS-MOD. In similar manner to the original OSeMOSYS formulation, all additions have been formulated as mostly separated blocks, as depicted in Figure D.2.

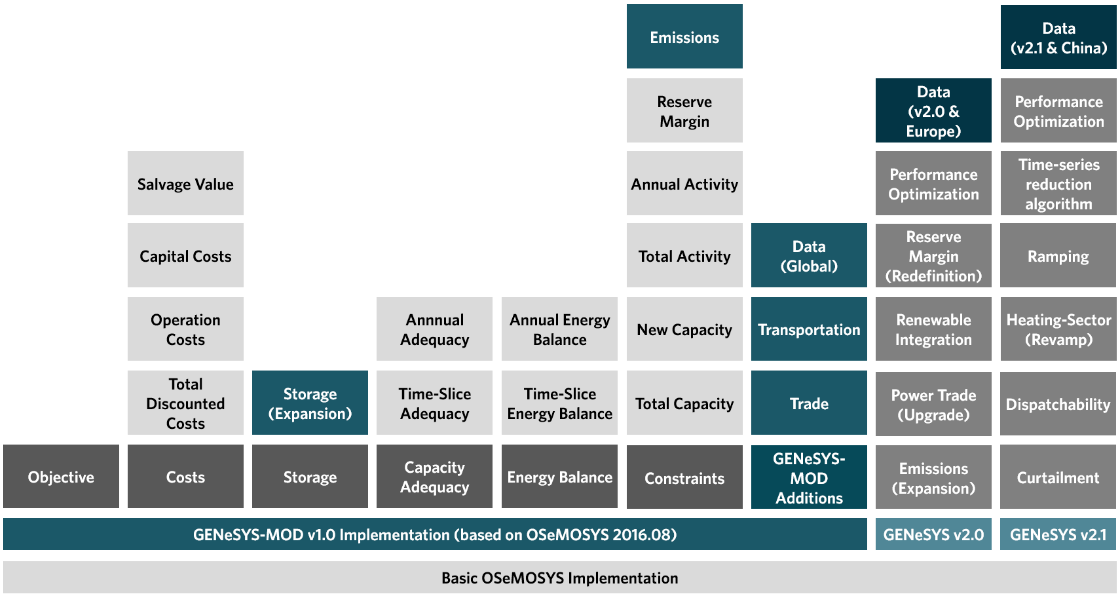

Figure D.2: Simplified block structure of OSeMOSYS and GENeSYS-MOD. The grey blocks on the right side represent recent additions to GENeSYS-MOD. Source: Own illustration.

In general, OSeMOSYS features several blocks of functionality that can be modified are expanded individually. Each of these blocks consists of one or multiple equations. In total GENeSYS-MOD considers 122 individual mathematical equations each set up for a variety of different sets. The main characteristics of an energy system are represented with energy balances (i.e., demand equals production plus/minus trade and storages) and capacity adequacies for all energy carriers. Yearly capacity addition limits, as well as total limits for capacities or technology activity, implement technological, economic, or physical boundaries of the analyzed system. Storages are modeled different from other technologies and thus feature their own block. The mathematical formulation of storages has been improved within GENeSYS-MOD compared to the basic OSeMOSYS formulation. Also, GENeSYS-MOD features an overhauled trade of energy carriers (e.g., electricity) with losses, costs, and endogenous capacity expansion. Additional equations for transportation carriers limit modal shifts between transportation services (e.g., air to rail). More recently, the power trade, as well as the integration of renewable generation technologies, has been expanded. For more detail regarding the additions of GENeSYS-MOD please refer to Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) and Burandt, Löffler, and Hainsch (2018).

### Mathematical formulation

This appendix gives an overview over the sets, variables, and parameters used in the mathematical formulation in section 5.4. These lists do not include all variables or parameter used by OSeMOSYS or GENeSYS-MOD. For a more comprehensive overview, please refer to Howells et al. (2011), Löffler, Hainsch, Burandt, Oei, Kemfert, et al. (2017) and Burandt, Löffler, and Hainsch (2018).

### Sets, variables and parameters

Sets

| Set | Description |
|---|---|
| $l \in L$ | Timeslices (hours) |
| $y \in Y$ | Years |
| $t \in T$ | Technologies |
| $f \in F$ | Fuels |
| $s \in S$ | Storage-Technologies |
| $r, rr \in R$ | Regions (provinces) |

Superscripts

| Superscript | Description |
|---|---|
| $first$ | Denotes the first entry in a set |
| $D$ | Denotes discounted costs |

Variables

| Variable | OSeMOSYS-Style Name | Description |
|---|---|---|
| $tc$ | TotalCost | Sum of technology and storage costs |
| $ttc$ | TotalTechnologyCosts | Sum of operating-, investment-, emission-, and ramping-costs minus the salvage value for any technology |
| $tsc$ | TotalStorageCost | Sum of fixed, variable, investment, emission, and ramping costs minus the salvage value for any storage |
| $atc$ | AnnualTotalTradeCosts | Yearly costs for trading fuels between regions |
| $acc$ | AnnualCurtailmentCost | Yearly costs for curtailment |
| $ncc$ | NewTradeCapacityCosts | Costs for added power trading infrastructure |
| $oc$ | OperatingCost | Sum of fixed and variable costs |
| $ci$ | CapitalInvestment | Capital expenditures |
| $ep$ | TechnologyEmissionsPenalty | Emission penalty or costs |
| $sv$ | SalvageValue | Salvage value of technology t in year y |
| $rc$ | AnnualProductionChangeCost | Annual ramping costs |
| $tcap$ | TotalCapacityAnnual | Total existing capacity of a technology in given region and year |
| $g$ | RateOfProductionByTechnology | It represents the quantity of fuel f that technology t would produce in one mode of operation and in time slice l, if the latter lasted the whole year |
| $g^{\Delta+}$ | ProductionChangeUp | Upwards change of generation |
| $g^{\Delta-}$ | ProductionChangeDown | Downwards change of generation |

Parameters

| Parameter | OSeMOSYS-Style Name | Description |
|---|---|---|
| $AF$ | AvailabilityFactor | Maximum time a technology can run in the whole year, as a fraction of the year |
| $CTA$ | CapacityToActivityUnit | Conversion factor relating the energy that would be produced when one unit of capacity is fully used in one year |
| $RF^{+}$ | RampingUpFactor | Fraction of capacity that can be activated each hour |
| $RF^{-}$ | RampingDownFactor | Fraction of capacity that can be deactivated each hour |
| $YS$ | YearSplit | Duration of a modelled time slice, expressed as a fraction of the year |
| $RCF$ | ProductionChangeCost | Costs for changing one unit of energy |
| $DR$ | DiscountRate | Discount rate for determining discounted costs that are included in the objective function |

#### D.2.0.1 Mathematical formulation with OSeMOSYS-style names

$$\begin{aligned} &RateOfProductionByTechnology_{y,l,t,f,r} \cdot YearSplit_{y,l} \\ &\quad - RateOfProductionByTechnology_{y,l-1,t,f,r} \cdot YearSplit_{y,l-1} \\ &\quad\quad = ProductionChangeUp_{y,l,t,f,r} \\ &\quad\quad\quad - ProductionChangeDown_{y,l,t,f,r} \quad \forall y,l,t,f,r \end{aligned} \tag{D.1}$$

$$\begin{aligned} &ProductionChangeUp_{y,l,t,f,r} \leq \\ &\quad TotalCapacityAnnual_{y,t,r} \cdot AvailabilityFactor_{y,t,r} \\ &\quad \cdot CapacityToActivityUnit_{t} \cdot RampingUpFactor_{r,t,y} \\ &\quad\quad \cdot YearSplit_{y,l} \quad \forall y,l,t,f,r \end{aligned} \tag{D.2}$$

$$\begin{aligned}
&ProductionChangeDown_{y,l,t,f,r} \leq \\
&\qquad TotalCapacityAnnual_{y,t,r} \cdot AvailabilityFactor_{y,t,r} \\
&\qquad \cdot CapacityToActivityUnit_{t} \cdot RampingDownFactor_{r,t,y} \\
&\qquad \cdot YearSplit_{y,l} \quad \forall y,l,t,f,r
\end{aligned} \tag{D.3}$$

$$\begin{aligned}
&AnnualProductionChangeCost_{y,t,f,r} = \\
&\qquad \sum_{l}\Big(ProductionChangeUp_{y,l,t,f,r} + ProductionChangeDown_{y,l,t,f,r}\Big) \\
&\qquad \cdot ProductionChangeCost_{r,t,y} \\
&\qquad \forall y,t,f,r
\end{aligned} \tag{D.4}$$

$$\begin{aligned}
&DiscountedAnnualProductionChangeCost_{y,t,f,r} = \\
&\qquad \frac{AnnualProductionChangeCost_{y,t,f,r}}{(1 + DiscountRate)^{y-StartYear+0.5}} \quad \forall_{y,t,f,r}
\end{aligned} \tag{D.5}$$

$$\begin{aligned}
&TotalDiscountedCostByTechnology_{y,t,r} = \\
&\qquad DiscountedOperatingCost_{y,t,r} \\
&\qquad + DiscountedCapitalInvestment_{y,t,r} \\
&\qquad + DiscountedTechnologyEmissionsPenalty_{y,t,r} \\
&\qquad + DiscountedAnnualProductionChangeCost_{y,t,r} \\
&\qquad - DiscountedSalvageValue_{y,t,r)} \quad \forall y,t,r
\end{aligned} \tag{D.6}$$

$$\begin{aligned}\text{minimize } z = &\\ &\sum_{y,r}\Bigg(\sum_{t}\Big(TotalDiscountedCostByTechnology_{y,t,r)}\Big)\\ &\quad+\sum_{s}\Big(TotalDiscountedStorageCost_{y,s,r)}\Big)\\ &\quad+DiscountedAnnualTotalTradeCosts_{y,r)}\\ &+\sum_{f,rr}\Big(DiscountedNewTradeCapacityCosts_{y,f,r,rr)}\Big)\\ &\qquad+\sum_{f}\Big(DiscountedAnnualCurtailmentCost_{y,f,r}\Big)\Bigg) \qquad \text{(D.7)}\end{aligned}$$

## Appendix E

# Appendix to Chapter 6: Necessity of hydrogen imports for decarbonizing Japan's energy system

## E.1 Transport sector results

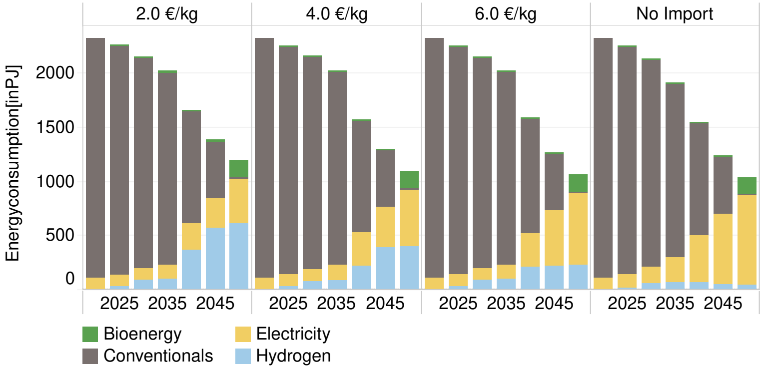

Figure E.1: Development of the transportation sector in the case without hydrogen imports compared the case with hydrogen imports priced at 2€/kg.

As shown in Figure E.1, cheap hydrogen imports allow for a substantial increase in hydrogen usage in the transportation sector. Furthermore, utilizing hydrogen will slightly increase the final consumption in the transportation sector, as hydrogen-fueled transportation technologies are less efficient compared to technologies directly utilizing electricity. In both cases, an increase in transportation via rail can be observed. Power-To-Liquid fuels are considered in

## E.2 Model validation graphs

The model results for the base year have been validated by data available from the International Energy Agency (IEA) and the Japanese Ministry of Economy, Trade and Industry (METI) (compare Figures E.2 and E.3.

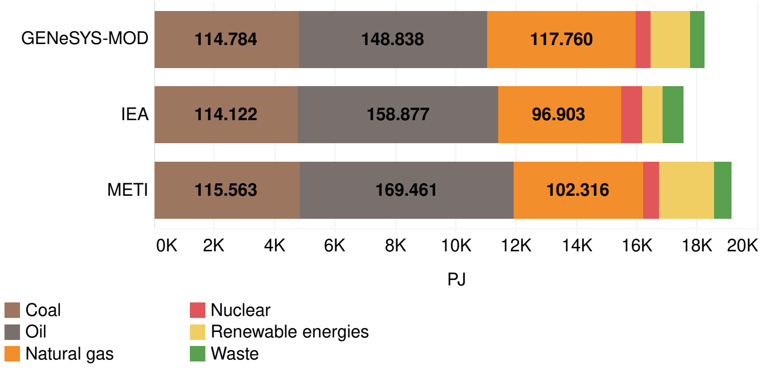

Figure E.2: Comparison of GENeSYS-MOD primary energy consumption results for 2019 with data from METI and IEA.

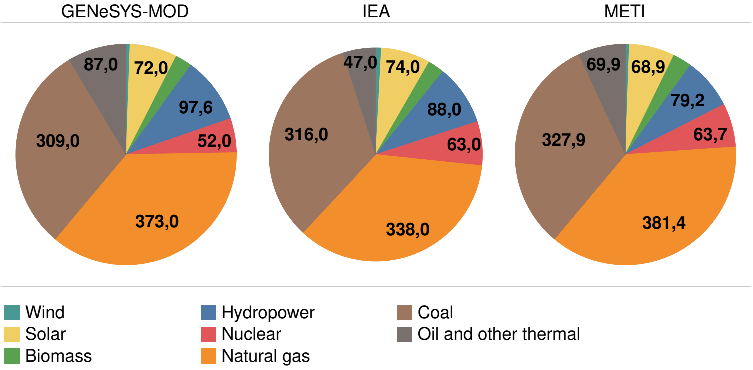

Figure E.3: Comparison of GENeSYS-MOD power generation results for 2019 with data from METI and IEA.

## E.3 Dispatch model

In the following subsections, the mathematical equations of the dispatch model are displayed. The utilized sets, variables, and parameters are presented in Tables E.1–E.3.

Table E.1: Sets of the dispatch model

| Set | Element | Description |
|---|---|---|
| $\mathfrak{H}$ | $\ni h$ | Hour |
| $\mathfrak{R}$ | $\ni r, \ni rr$ | Region |
| $\mathfrak{P}$ | $\ni p$ | Dispatchable Power Plants |
| $\mathfrak{I}$ | $\ni i$ | Non-Dispatchable Power Plants |
| $\mathfrak{S}$ | $\ni sto$ | Storage Technologies |

Table E.2: Parameters of the dispatch model

| Parameter | Description |
|---|---|
| $vc_{r,p}$ | Variable costs |
| $dem_{r,h}$ | Demand in hour h |
| $p_{r,p}^{inst}$ | Installed capacity of power plant p |
| $i_{r,i}^{inst}$ | Installed capacity of variable power generator i |
| $cf_{r,i,h}$ | Capacity factor of var gen i in hour h |
| $sto_{r,sto}^{inst,e}$ | Installed storage energy capacity |
| $sto_{r,sto}^{inst,p}$ | Installed storage power capacity |
| $sto_{sto}^{eff}$ | Storage roundtrip efficiency |
| $rf_p$ | Ramping factor: Allowed (de)activation of conventional capacity per hour |
| $t_{r,rr}^{cap}$ | Power trade capacity from regions r to rr |
| $co2_p^{act}$ | Carbon intensity of power plant |
| $co2^{price}$ | Carbon price |
| $inf^{penalty}$ | Infeasibility Penalty |
| $\varepsilon$ | Machine epsilon |

Table E.3: Variables of the dispatch model

| Variable | Description |
|---|---|
| $Z$ | Objective variable |
| $G_{r,p,h}$ | Dispatchable generation |
| $G^{inf}_{r,h}$ | Infeasibility generation |
| $G^{up}_{r,p,h}$ | Upwards change in dispatchable generation |
| $G^{up}_{r,p,h}$ | Downwards change in dispatchable generation |
| $V_{r,i,h}$ | Non-Dispatchable generation |
| $ST^{in}_{r,sto,h}$ | Storage charging |
| $ST^{out}_{r,sto,h}$ | Storage discharging |
| $SOC_{r,sto,h}$ | Storage state-of-charge |
| $CURTAIL_{r,h}$ | Curtailed load |
| $FLOW^{pos}_{r,rr,h}$ | Positive trade flow from regions r to rr |
| $FLOW^{neg}_{r,rr,h}$ | Negative trade flow from regions r to rr |
| $FLOW_{r,rr,h}$ | Net trade flow from regions r to rr |

## Objective function

$$\begin{aligned}
Z = &\sum_{r,p,h} G_{r,p,h} \cdot vc_{r,p} \\
&+ \sum_{r,p,h} G_{r,p,h} \cdot co2^{act}_{p} \cdot co2^{price} \\
&+ \sum_{r,sto,h} ST^{out}_{r,sto,h} \cdot \varepsilon \\
&+ \sum_{r,h} LOSTLOAD_{r,h} \cdot \varepsilon \\
&+ \sum_{r,rr,h} (FLOW^{pos}_{r,rr,h} + FLOW^{neg}_{r,rr,h}) \cdot \varepsilon \\
&+ \sum_{r,h} G^{inf}_{r,p,h} \cdot inf^{penalty}
\end{aligned} \tag{E.1}$$

## Energy balance

$$\begin{aligned} &\sum_{p} G_{r,p,h} + G^{inf}_{r,h} + \sum_{i} V_{r,i,h} \\ &\sum_{sto} ST^{out}_{r,sto,h} - \sum_{sto} ST^{in}_{r,sto,h} + \sum_{rr} FLOW_{rr,r,h} \\ =&dem_{r,h} + CURTAIL_{r,h} \quad \forall r, h \end{aligned} \tag{E.2}$$

## Power Generation

Power generation for dispatchable generators is limited by the installed capacity, whereas for variable renewable generators, the production has to equal the installed capacity times the hourly capacity factor.

$$G_{r,p,h} \leq p^{inst}_{r,p} \quad \forall r, p, h \tag{E.3}$$

$$Vr, i, h = i^{inst}_{r,i} \cdot cf_{r,i,h} \quad \forall r, i, h \tag{E.4}$$

## Storages

The following equations represent the storage formulation included in the dispatch model.

$$\begin{aligned} SOC_{r,sto,h} = &\, SOC_{r,sto,h-1} \\ &+ \frac{1 + sto^{eff}_{sto}}{2} ST^{in}_{r,sto,h} \\ &- \frac{2}{1 + sto^{eff}_{sto}} ST^{out}_{r,sto,h} \quad \forall r, sto, h \end{aligned} \tag{E.5}$$

$$ST^{in}_{r,sto,h} \leq sto^{inst,p}_{r,sto} \quad \forall r, sto, h \tag{E.6}$$

$$ST^{out}_{r,sto,h} \leq sto^{inst,p}_{r,sto} \quad \forall r, sto, h \tag{E.7}$$

$$ST^{out}_{r,sto,h} \leq SOC_{r,sto,h-1} \quad \forall r, sto, h \tag{E.8}$$

$$ST^{in}_{r,sto,h} + SOC_{r,sto,h-1} \leq sto^{inst,e}_{r,sto} \quad \forall r, sto, h \tag{E.9}$$

## Ramping

The following equations present the ramping constraints for dispatchable power generators.

$$Gr,p,h - G_{r,p,h-1} = G^{up}_{r,p,h} - G^{down}_{r,p,h} \quad \forall r,p,h \tag{E.10}$$

$$G^{up}_{r,p,h} \leq p^{inst}_{r,p} \cdot rf_p \quad \forall r,p,h \tag{E.11}$$

$$G^{down}_{r,p,h} \leq p^{inst}_{r,p} \cdot rf_p \quad \forall r,p,h \tag{E.12}$$

## Trade

The power trade formulation is generally based on a net-trade/net-flow formulation, with the raw-flow components ($FLOW^{pos}_{r,rr,h}$ and $FLOW^{neg}_{r,rr,h}$) only used in the objective function.

$$FLOW_{r,rr,h} = -FLOW_{rr,r,h} \quad \forall r,rr,h \tag{E.13}$$

$$FLOW_{r,rr,h} \leq t^{cap}_{r,rr} \quad \forall r,rr,h \tag{E.14}$$

$$FLOW_{r,rr,h} \geq -t^{cap}_{r,rr} \quad \forall r,rr,h \tag{E.15}$$

$$FLOW_{r,rr,h} = FLOW^{pos}_{r,rr,h} - FLOW^{neg}_{r,rr,h} \quad \forall r,rr,h \tag{E.16}$$

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