Emission Pathways Towards a Low-Carbon Energy System for Europe: A Model-Based Analysis of Decarbonization Scenarios

Karlo Hainsch,[a] Thorsten Burandt,[b] Konstantin Löffler,[c] Claudia Kemfert,[d] Pao-Yu Oei,[c] and Christian von Hirschhausen[c]

ABSTRACT

The aim of this paper is to showcase different decarbonization pathways for Europe with varying Carbon dioxide (CO_2) constraints until 2050. The Global Energy System Model (GENeSYS-MOD) framework, a linear mathematical optimization model, is used to compute low-carbon scenarios for 17 European countries or regions. The sectors power, low- and high- temperature heating, and passenger and freight transportation are included, with the model endogenously constructing capacities in each period. Emission constraints differ between different scenarios and are either optimized endogenously by the model, or distributed on a per-capita basis, GDP-dependent, or based on current emissions. The results show a rapid phase-in of renewable energies, if a carbon budget in line with established international climate targets is chosen.

It can be shown that the achievement of the 2° target can be met with low additional costs compared to the business as usual case, while reducing total emissions by more than 30%.

Keywords: Decarbonization, Energy System Modeling, GENeSYS-MOD, Renewables, Energy Policy, Energy Transition

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1. INTRODUCTION

One of the biggest contributors of greenhouse gas (GHG) emissions is the energy sector, accounting for more than two thirds of the global emissions (IEA, 2018). On a global scale, GHG emissions in the energy and industrial sector amounted to about 39 gigatonnes of CO_2 equivalent in 2017 (IEA, 2018), a number which has to be lowered substantially if climate targets are meant to be met (IPCC, 2018). Therefore, various challenges arise for different countries when it comes to decarbonize their energy systems. The European Union (EU), being a major economic force, has set several climate goal targets, which should lead to an energy system with almost no GHG emissions (European Comission, 2018). Yet, no exact configuration of the energy system is defined, and countries have to promote their own policies to reach the goals. As a consequence, these policies are not necessarily elaborated with one common European goal in mind but rather conflicting national ones.

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In recent years, the focus was heavily set on decarbonizing the electricity sector (Gerbaulet et al., 2019; Child et al., 2019; Hansen et al., 2019; Jenkins et al., 2018). A high degree of electrification in these sectors is predicted in future scenarios, which implicitly affects the power sector. Since the current penetration of renewables in the electricity sector differs substantially between European countries, different challenges arise. While some countries need to tackle a complete overhaul of their mainly on fossil fuels relying electricity sector, others face the effects of increasing demands or limited potentials for renewable energies (European Comission, 2018). Moreover, the European Union faces the particular challenge of having declared climate targets for the whole Union but the economic development of the individual member states as well as the regions affected by structural change in the energy sector must be taken into account.

Therefore, this paper analyzes the impact of different emission allocation methods on the European energy system and its transition towards less carbon intensity, with a special emphasis on the interaction between the different sectors. In the next chapter, the current state of the art of energy system modeling is highlighted. A brief overview of the Global Energy System Model (GENeSYS-MOD) and relevant data input is provided, followed by the scenario definition and emission allocation methods. Afterwards, the different results are shown and discussed and a brief conclusion is drawn. A preliminary version of this work was also published as a DIW Discussion Paper (Hainsch et al., 2018)

2. STATE OF THE ART

The field of energy system modeling experienced a substantial increase in interest over the last decades. Recent political debates, coupled with the required advances in computational power, lead to numerous studies and papers. Yet, traditionally, the power sector is by far the most widespread sector of choice when it comes to analyzing energy system transitions towards less GHG emissions. Several studies focus on the European electricity sector and analyze impacts of high renewable penetration (Scholz, 2012; PwC, 2011; Czisch, 2007; Plessmann and Blechinger, 2016). Scholz (2012) and Czisch (2007) come to similar results regarding the technical and economic feasibility of such electricity sectors. Plessmann and Blechinger (2016) suggest that such a system, which would meet the 2050 EU emission reduction target, can be achieved with investments of 403 billion Euro (EUR), increasing levelized cost of electricity (LCOE) by about 35%. These models provide excellent temporal and spatial resolution, which allow for a more detailed analysis of the electricity sector than what energy system models can achieve. However, the effects of other sectors are defined exogenous and, thus, no interactions are modeled. Moreover, examples show that lowering the temporal resolution does not necessarily impact the results significantly (Welsch et al., 2012; Blanford et al., 2018).

Energy system models incorporate two or more sectors at the same time. On the one hand, this gain in complexity results in a loss of accuracy and often requires more assumptions to be made. On the other hand, it acknowledges the energy system as whole and highlights sector coupling. As GENeSYS-MOD can be classified as a bottom up model (Löffler et al., 2017), we will highlight the most commonly used models of this kind and outline the differences.

Generally, the most common used bottom up models belong to the MARKet ALlocation (MARKAL) and the Model for Energy Supply Alternatives and their General Environmental Impacts (MESSAGE) family of models (Subramanian et al., 2018). MARKAL and its su ccessor The Integrated MARKAL-EFOM System (TIMES) were developed as part of the IEA-ETSAP (Energy Technology System Analysis Program) and newer versions combine a technical and economic approach. Similarly, MESSAGE links, through different modules, technological and macroeconomic developments to gain insights into future energy systems. This linkage, however, leads to a significant increase in complexity, which leads to lower spatial or temporal resolution compared to GENeSYS-MOD. Moreover, data and/or source codes are not necessarily publicly available.

On a European scale, the PRIMES framework is the predominant one, being used also by the European Commission for impact assessment and analysis of policy options. The framework was used in the EUCO27 and EUCO30 policy scenarios on the basis of the EU Reference Scenario 2016. In their latest report, the European Comission (2018) uses the PRIMES framework to address pathways for the European energy system in line with the 2°C and 1.5°C scenarios. While the 2° C scenario aims for 80% GHG reduction compared to 1990, full decarbonization is required for keeping global mean temperature below 1.5°C. Moreover, an high amount of sector coupling leads to an increased electricity demand across all scenarios, which in some cases surpasses double of the current demand. However, the study does not assess the question of how to allocate the emission to the different member states. In addition, while the PRIMES framework is very rich in technological detail and combines it with behavioral modeling which follows micro-economic foundations (E3M-Lab, 2018), a general point of criticism is the lack of transparency, both in the formulation of the scenarios and the underlying assumptions used to compute the results.

The earlier mentioned TIMES framework is also used in several studies which address the European energy system or parts of it. Nijs et al. (2018) conclude that either a combination of carbon capture and storage (CCS) or nuclear power or large amounts of renewable generation technologies are required to fulfill climate targets. In addition, they highlight the role of electrofuels in the context of sector coupling for those sectors without easy options of electrification. Others improved the representation of single sectors, like the residential (Chiodi et al., 2017) or transportation sector (Thiel et al., 2016), have certain regional focuses (Zeyringer et al., 2013), or use the framework to perform sensitivity analyses on common assumption (Nijs et al., 2015). Other work in the European context includes a study by Ram et al. (2018), proving that a European energy system which is based on 100% renewable energies is feasible, considering all energy sectors. Electricity demand increases by factor 4, yet the system cost are not higher than for the current configuration of the European energy system. As a downside, the model does not optimize inter-temporally, but rather optimizes each period individually.

As shown, various modeling frameworks have been developed in recent time to analyze energy systems. Their ability of assisting in the development of policies and long term planning of energy systems are highlighted by their increasing usage from institutions and researchers. A lot of work has been done in the European context, driven by the European Commission and researchers, in showcasing how the energy transition towards less GHG emissions could develop. However, the studies generally do not deal with the question of how different emission allocation methods affect the single countries. Moreover, the used frameworks are mostly nontransparent in their underlying model and scenario assumptions. Therefore, this work aims to bridge that research gap, providing an analysis of the feasibility of different emission distribution and climate scenarios, while providing a fully open source code. The underlying research question is what the underlying implications of different carbon constraints are on a future low-cost energy system in Europe.

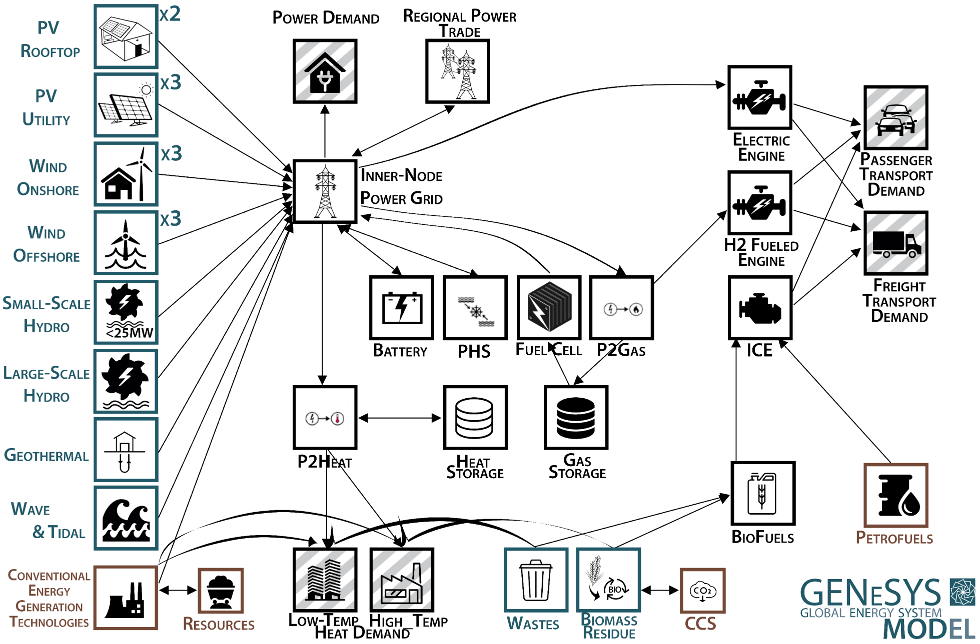
3. MODEL AND DATA

3.1 General model description

The model for analyzing the research questions is based on the formulation of the Global Energy System Model (GENeSYS-MOD), as described by Löffler et al. (2017) and Burandt et al. (2018).

In essence, GENeSYS-MOD can be illustrated as a flow-based inter-temporal cost-optimization model. The different nodes are represented as *Technologies*, which are connected by *Fuels*. Examples for *Technologies* are production entities like wind or solar power, conversion technologies like heat pumps, storages, or vehicles. *Fuels* serve as connections between these technologies and can be interpreted as the arcs of the network. In general, *Fuels* represent energy carriers like electricity or fossil fuels, but also more abstract units like demands of a specific energy carrier or areas of land are classified as *Fuels*. Also, *Technologies* might require multiple different *Fuels* or can have more than one output fuel. As an example, a combined heat and power plant could use coal as an input fuel and produce electricity and heating energy as an output fuel. Efficiencies of the technologies are being accounted for in this exact process, which would allow to model energy losses due to conversion. Energy demands are classified into three main categories: electricity, heating, and transportation. They are exogenously defined for every region and each year. The model then seeks to meet these demands through a combination of *Technologies* and trade between the different regions. For that purpose, investments into capacities are required in future time periods and are allowed for all technologies, as well as for power transmission capacities. Figure 1 gives a general overview of the different *Technologies* and the connections between them.

Figure 1: Stylized model structure of GENeSYS-MOD v2.0.



GENeSYS-MOD v2.0 offers a fully updated data set for all global parameters, such as fuel prices, general cost assumptions, and emissions data.[1] Furthermore, the list of available technologies has been revised and extended, now including more options in the transportation sector, as well as a representation of CCS plants. Additionally, the model has been upgraded with new equations and revised formulations that offer more and new functionalities.The chosen regional disaggregation of Europe with 17 nodes in total leads to a stylized version of the European electricity grid. The

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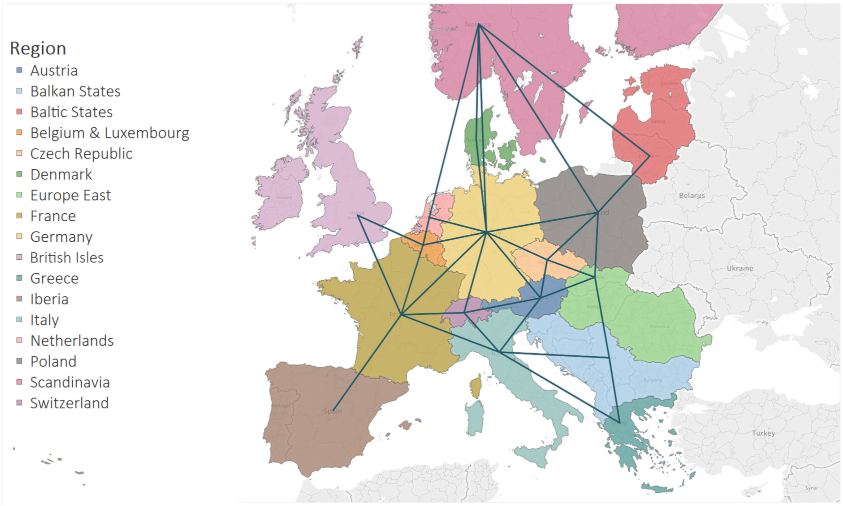
1. With 2015 as the reference year.

resulting grid structure with its possible connections between nodes can be found in Figure 2. The temporal resolution has been increased from 6 to 16 time slices per year, now featuring all four quarters of a year, with four daily time slices.

Figure 2: Grid structure and spatial set-up for Europe.



For a detailed overview of all changes and additions, please consult the supplementary material. For changes in the model formulation in the second version of GENeSYS-MOD, both for model and data, can be found in Burandt et al. (2018).

4. SCENARIO DEFINITION

A comparison of a single, European, limit (which is optimally allocated by the model), and different regional allocations, is done, in order to identify the optimal distribution of the available CO_2 limit. This problem is of specific relevance to the present situation in Europe, as the strong importance of decarbonization in the political debate of energy transition is generally accepted. Nevertheless, the question of distributing the remaining available budgets and the country-specific allocations, while keepint in mind the unanimity principle of the EU, has to be clarified. Without any joint measures against climate change, and agreements from the individual national governments, reaching the target of keeping the rise of the global mean temperature below 2° Celsius is getting more and more difficult. Therefore, this paper tries to find answers to the question of national distributions of the available CO_2 limit and the fairest distribution for the European region. Also, to avoid additional uncertainties, all currently implemented national policies are taken into account, while those which are still being discussed are excluded.

The following three emission pathway scenarios were implemented:

- **1.5° C:** The model gets a strict CO_2 limit of 25.29 $GtCO_2$ for Europe. Considering the current annual CO_2 emissions of around 5.6 $GtCO_2$, this budget would be exhausted within the next four to five years. Therefore, immediate action would be required. This pathway serves as a probability study if, and under what conditions the target of keeping the global mean temperature rise below 1.5° C is possible.

- **2° C:** The scenario of keeping the temperature below 2° C is used to compare the different decarbonization pathways of the modeled European regions. It has a carbon budget of 51.60 $GtCO_2$. This emission pathway, coupled with a free, distribution of the European CO_2 limit is further referenced as the base scenario.
- **BAU:** In contrast to the previous scenarios, we do not assume any emission budget in this case. Rather, a carbon price in line with the New Policy scenario from the IEA (2016) is used. This scenario serves to analyze if a decarbonization[2] would still happen, even without an applied emission budget.

The German Advisory Council on Global Change (WBGU, 2009) promotes an emission per-capita approach of distributing the CO_2 budget. Hereby, a differentiation between a "historical responsibility" and a "responsibility for the future" concept has to be made. Whereas in the "historical responsibility" case, the total emissions from 1990 are used to determine the share for each country, the "responsibility for the future" utilizes only the current (2010) emissions per capita for this calculation. Considering the relatively homogeneous historical development regarding CO_2 emissions within Europe (compared to a global analysis), both approaches would only differ in small amounts. Therefore, we use the values from our base year 2015 as key-indicators. Staying in the definitions by the German Advisory Counsil on Global Change (WGBU), we look at scenarios within the "responsibility for the future" approach.

Furthermore, we consider four different emission distribution scenarios as follows:

- **Regional Limit / Free Distribution:** No fixed share of the European CO_2 budget is included in the model run, and therefore the model can endogenously decide for the cost-optimal allocation of the emissions.
- **Share by GDP:** In this scenario, the 2015 gross domestic product (GDP) of each country is used as a key indicator to distribute the available budget.
- **Share by current emissions:** The emissions from the base year 2015 are used to define the share for the available budget.
- **Share by population:** Here, the available budget is shared between the modeled regions with respect to their population in the year 2015.

To define these distributions, several national key indicators were used. Considering the possible combinations of these scenario types, a total of 9 different scenarios are defined: four scenarios with a 2° C climate target (distribution of CO_2-budget: free, by GDP, by current emissions, and by population), four scenarios with a 1.5° C climate target (distribution of CO_2-budget: free, by GDP, by current emissions, and by population), and the BAU scenario, where no budget is applied.

For distributing the emissions to our model regions, data available from The World Bank was used. Using data and assumptions, the regional shares, as seen in Figure 3, were calculated. In relative terms, the biggest differences are present in the Balkan states, Czech Republic, and Poland, all of which show a high CO_2-emissions to GDP ratio.

The importance of burden sharing can be illustrated using the example of system transforma- tion in Poland. Energy from coal has played and will play a vital role in the Polish energy economy. If allocated according to GDP, Poland would still receive 1.4 billion tons of CO_2 budget until 2050; on the other hand, if it were allocated according to historical emissions, the budget would be 4.3 billion, more than three times as much. Accordingly, distributing the emissions in different

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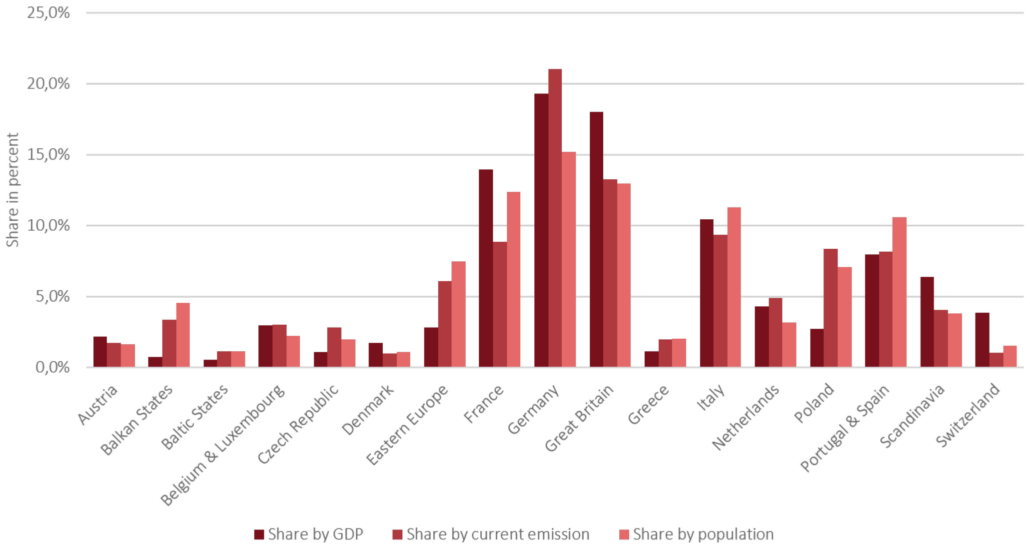
[2] Decarbonization meaning a full or almost full disappearance of fossil fuels in the energy system. Online Reference: https://data.worldbank.org/.

Figure 3: Calculated emission shares in the different distribution scenarios. Based on The World Bank.



ways could be particularly difficult for Poland and would have to be accompanied by parallel instruments for regional development and structural change.

5. RESULTS AND DISCUSSION

5.1 Emission pathway: 2° C

This section analyzes the results for the scenario, where the emission budget is derived from the 2° pathway. Also, the allocation of these emissions is not constrained, showcasing the ideal case, where a centralized planner is able to optimize.

Starting with the power sector, Figure 4 shows the electricity generation pathway, summed up over all modeled regions. As a general trend, it can be seen that starting in the year 2020, renewable technologies continuously replace fossil-fueled generation. By 2040, almost all electricity generation is provided by the combination of photovoltaic (PV), onshore wind, and hydropower.

When examining fossil fuels in depth, some interesting developments can be observed. Both hard coal and lignite are facing a constant phase-out across all regions. The reason for that lies in the fact that the emission budget is tight enough to force a rapid phase-out of these CO_2-intensive technologies. Natural gas, on the other hand, experiences a slight increase of importance in the power sector between 2015 and 2020, only to be phased out afterwards at a similar pace as the coal technologies. Nevertheless, no additional gas capacities are built as already existing ones are being used. Figure 17 in the Appendix can be consulted for further information on new capacities. This also implies that no capacities are built later would become stranded assets, since the integrated temporal approach of the model takes these effects into account.[3] The early growth in gas-based electricity production is tied to a substantial rise in total generation, which originates from demand increases and the beginning of the electrification of the other sectors. By 2040, both natural gas and

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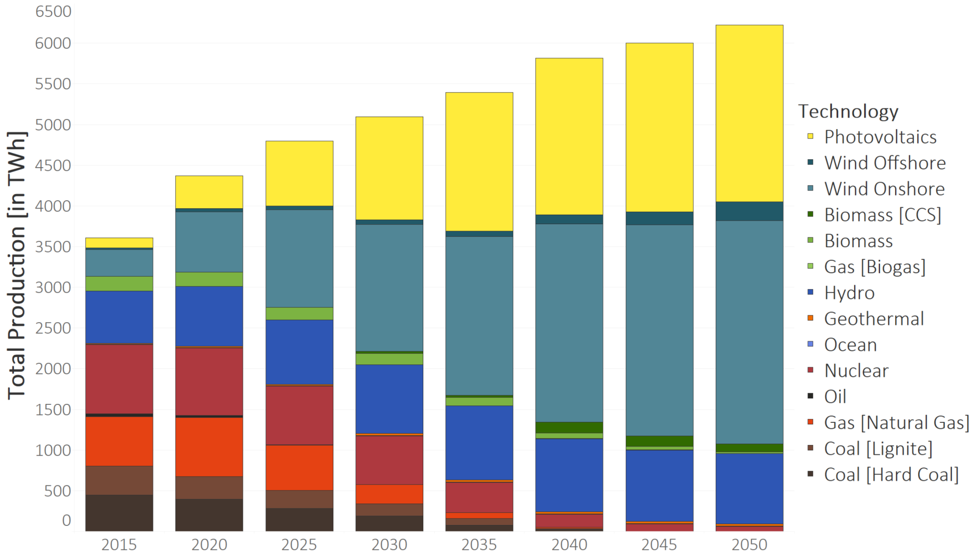
[3] For further information about stranded assets in the context of energy system modeling please refer to Löffler et al. (2019).

coal are almost nonexistent in the power sector. Nuclear energy is the only conventional generation technology that survives until 2050, although its share steadily diminishes as no new investments take place and existing capacities reach their end of life.

As for renewable energy sources, onshore wind, PV, and hydro power are the predominant technologies in Europe. PV and wind experience rapid increases in generation capacities between the modeled periods. Onshore wind appears to have the upper hand, where high potentials, an already very mature technology, and favorable cost developments enable high shares. In the final electricity mix of 2050, it accounts for about 47% of the total generation. Solar PV offers a similar development, the only notable difference being the lower potential, leading to upper limits being reached faster. Hydropower behaves slightly different than the two other technologies, since potentials are already quite used up, without much room for growth. Other renewable generation technologies, such as offshore wind, biogas or -mass, and geothermal energy are produced in small amounts compared to the aforementioned three technologies.

Figure 4: Development of yearly power production in the base scenario.



Comparing the power production of the various regions, different developments can be observed, as illustrated in Figure 5. Germany, for example, relying heavily on hard coal and lignite, will cut down its fossil power production by half until 2030, despite increasing the overall electricity generation. Since most of the assumed wind and PV potentials are already utilized by 2030, Germany's electricity production will decrease between 2030 and 2050. The British Isles, on the other hand, will phase out high shares of its natural gas-based power plants and switches to onshore wind generation instead. In the years from 2030 until 2050, the British Isles add solar PV plants to its energy mix, in addition to further increasing its onshore wind power production. Whereas most of Europe utilizes wind power as their primary energy source, the southern regions, such as Italy or the Iberian Peninsula, are relying on high shares of PV in the later time periods due to better radiation conditions.

The overall electricity production is increasing by about 81% between 2015 and 2050, which is a result of higher degrees of sector coupling and electrification of the other sectors. Taking a look at one of these sectors, the heating sector, and analyzing its development, the movement of

Figure 5: Power production profiles for Germany, British Isles, and Portugal and Spain in the years 2015, 2030, and 2050 in the base scenario.

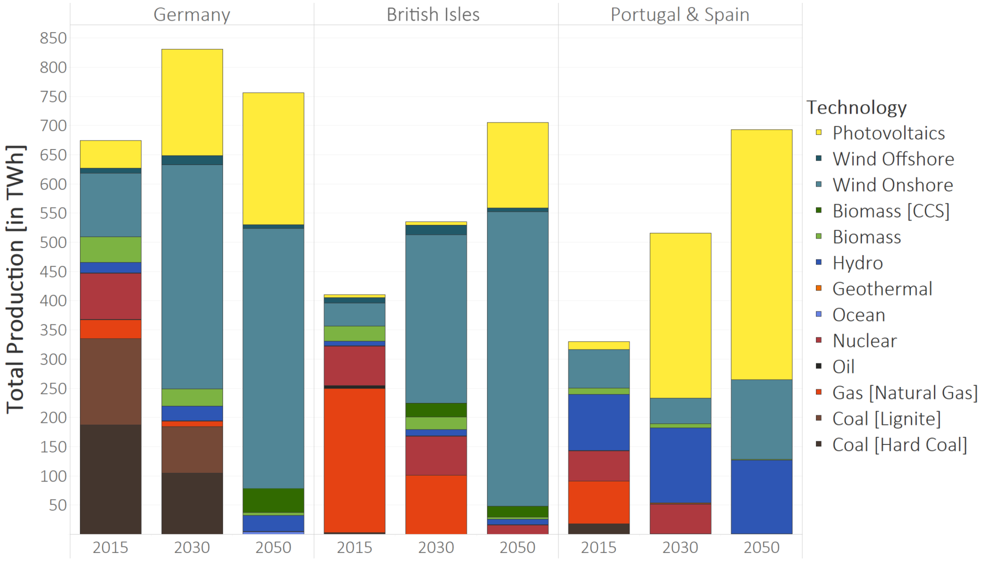
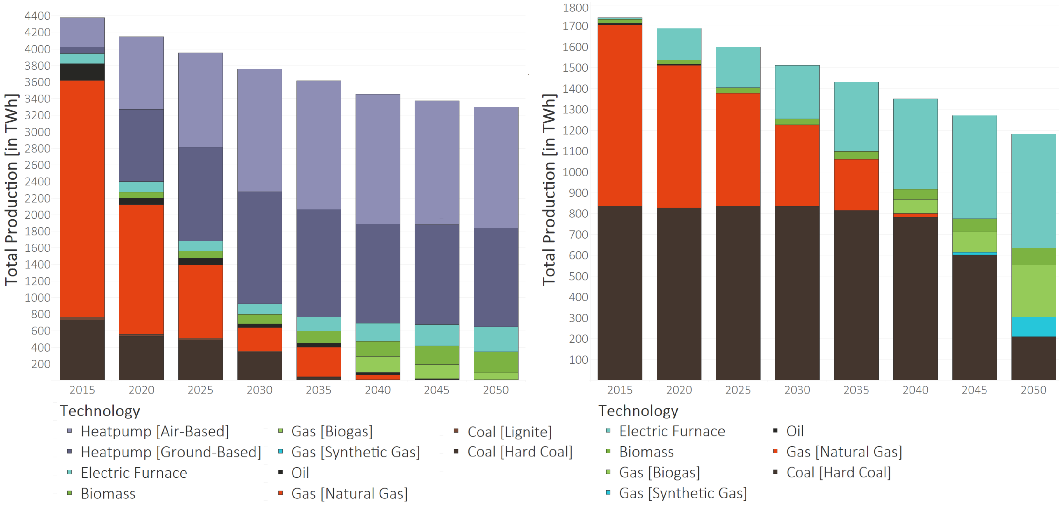


Figure 6: Yearly low-temperature (left) and high-temperature (right) heat production in the base scenario.



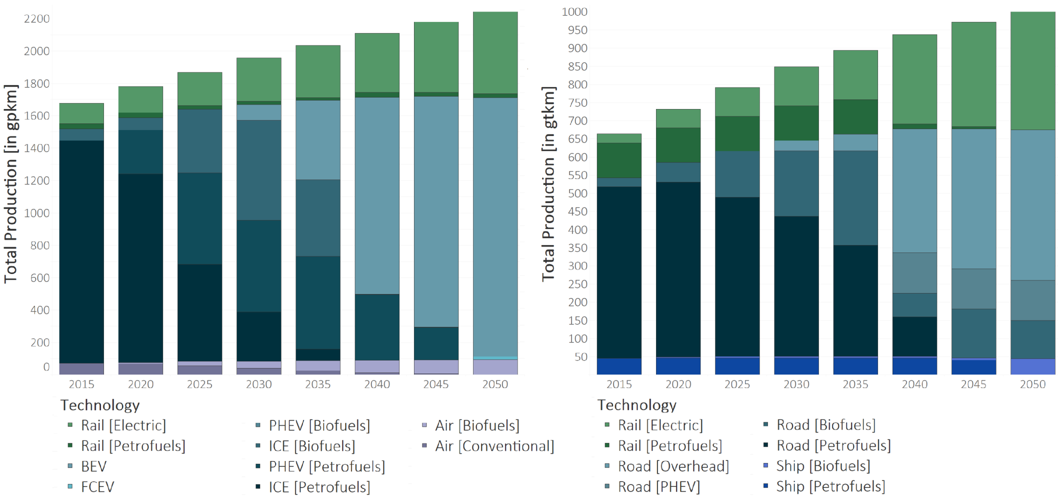
additional amounts of power becomes to light. In Figure 6 the pathways of low- and high-temperature heating energy are shown. As before, conventional technologies are grouped in the bottom of the figure, while new, low-carbon, technologies are shown in the top part of the graph.

Currently, natural gas is the most significant energy carrier in the low-temperature heating sector, accounting for more than 65% of the total production. This share, however, is decreasing rapidly when the decarbonization of the energy system is taken seriously. Within the first ten years, the amount of heating provided by natural gas is more than halved, and, by 2040 natural gas has vanished. The same can be said for coal and oil, which are basically removed from the low-temperature heating sector at the end of 2040.

The high-temperature heating sector is the most difficult to decarbonize. Figure 6 illustrates that this sector has a very high reliance on conventional energy sources such as natural gas and coal. Most of the gas-based heating is replaced with biogas between 2035 and 2040, where the existing gas-based heating facilities experience a sudden fuel switch. A steady replacement of gas-based plants with electric furnaces further decreases emissions, although coal stays in the energy mix, even in 2050. Regarding efficiency and costs, high-temperature heating with hydrogen (H_2) does not become a viable option in the 2° C pathway. In the years from 2050 on, however, a shift towards H_2 could likely be observed. Also, with decreasing costs of power generation, electric furnaces could become an even more prominent technology.

Figure 7 shows the resulting modal shares from 2015 until 2050 for both transportation sectors. In the passenger transportation sector, an early adoption of plug-in hybrid electric vehicles (PHEVs), fueled with conventional petrofuels can be observed in 2025. Furthermore, fully electric trains gain substantially in importance. In the second quarter of the century, biofuels gain in importance, becoming the main fuel for internal combustion engine (ICE) vehicles and PHEVs. This leads to substantial reductions of GHG emissions in the passenger transportation sector by 2035. Only in later time periods, fully electric battery electric vehicles (BEVs) start to replace conventional vehicles, whereas the newer PHEVs are switching from petro- to biofuels. Due to the decreasing costs of electricity, BEV are becoming the primary provider of passenger transportation services from 2040 on. Additionally, air transport faces a steady shift towards biofuels, coupled with a decreasing share of passenger transportation via airplanes. Thus, the passenger transportation sector is nearly decarbonized by 2050, with only small remnants of Diesel-electric trains remaining.

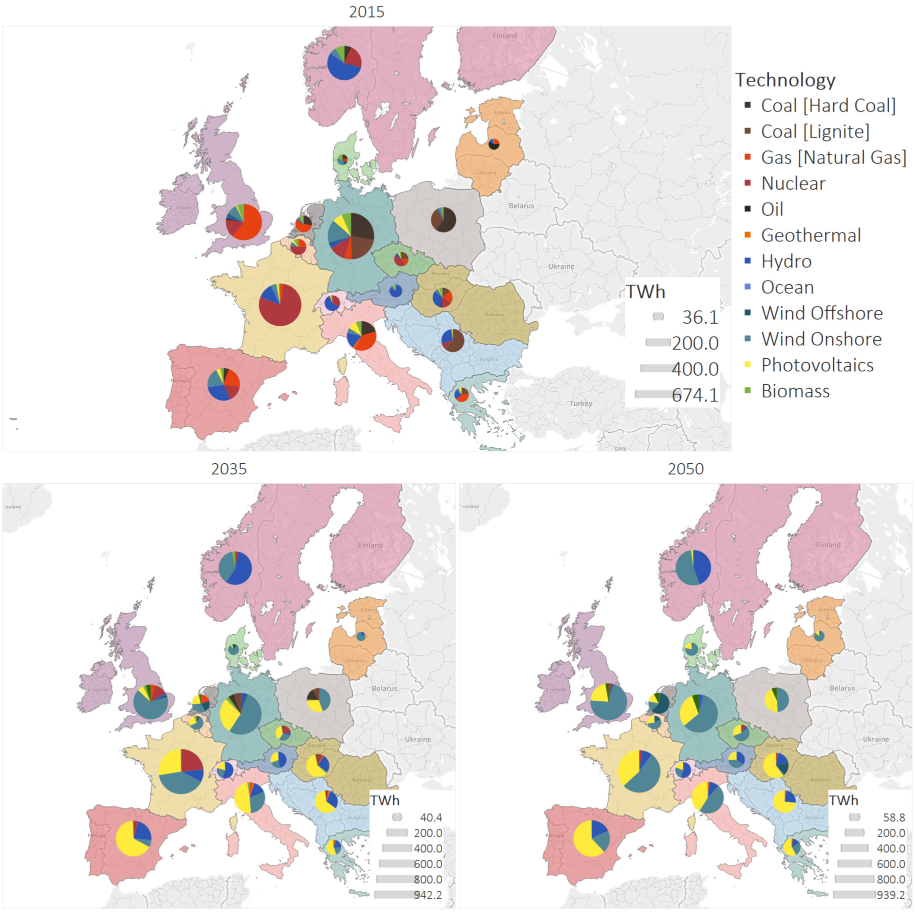
Figure 7: Development of passenger transportation services (left) and freight transportation services (right) in the base scenario.



In contrast, a high reliance on fossil fuel-based ICEs can be seen in the freight transportation sector, even in the 2030s.

With respect to freight transportation, trains, which are currently mostly diesel-electric, stay largely fossil fuel-driven until 2040, facing a rapid shift towards cleaner alternatives only in the last decade. Road-based transportation experiences a steady phase-in of biofuels, which peaks in 2035, with a percentage of 50% of all heavy goods vehicle (HGV) transports. Afterwards, a fast introduction of trolley-trucks can be observed. Those are powered by electric overhead lines and are thus a fully electric transportation technology, becoming the dominant technology in 2050. Conventional fuels are the main fuel for water-based freight transportation until 2045, but are entirely phased-out in 2050 and replaced with biofuels. Concluding, similar to the passenger transportation sector, freight transportation is about 95% decarbonized by 2050, due to high shares of electric HGV and biofuels.

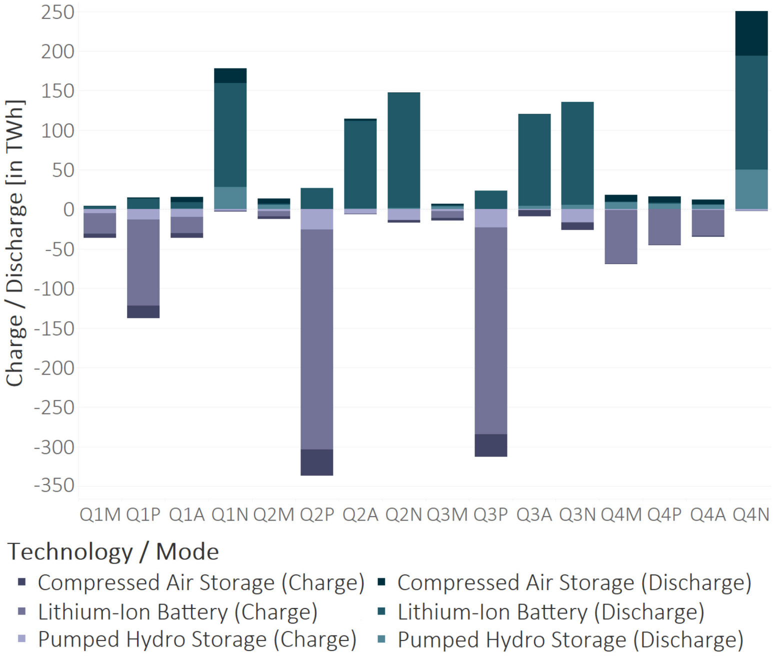
Figure 8: Regional power production for the years 2015, 2035, and 2050 in the base scenario.



On a regional level, it can be seen in Figure 8 that especially northern countries are quickly integrating capacities of onshore wind into their power generation, whereas the southern, Mediterranean, regions are utilizing higher shares of solar PV in 2035. This trend is continued until 2050, where the alternative technology is constructed more, due to the limitations of potentials that have been reached previously.

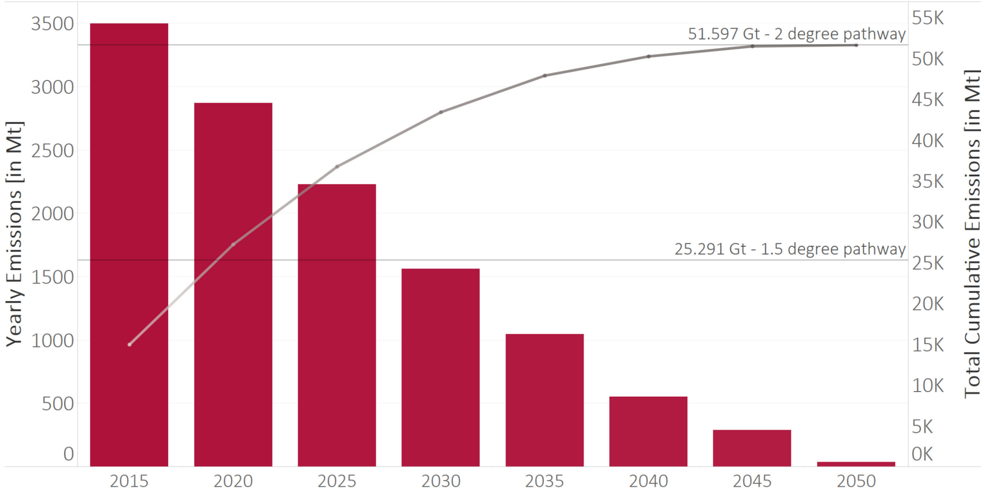
Observing the high shares of renewable energy sources (RES) in 2050, their variability and flexibility have to be considered. Therefore, storages play an important role of balancing these loads. Figure 9 shows the charging and discharging profiles of electric storages in the different time slices for the year 2050. The backbone of the European storage capacities are lithium-ion batteries that are only capable of providing intra-day storage possibilities. Energy stored in the peak-time of a day will therefore be used as an auxiliary energy-source in the night, to provide a stable energy generation. Compressed air energy storages (CAESs) and pumped hydro storages (PHSs) are used

Figure 9: Charge and discharge of electric storages in 2050 in the base scenario (per time slice).



Notes: The nomenclature for the timeslices is as follows: the year is separated in four quarters (e.g. Q1, Q2, ...), with four daily timebrackets each (morning (M), peak (P), afternoon (A), night (N). In combination, these stand for the specific time slice of the year, with e.g. Q3M representing the morning hours of the 3rd quarter of the year.

Figure 10: Annual CO2 emissions (left) and cumulative CO2 emissions (right) in the 2° C pathway.



as seasonal energy storages. Their stored energy is mostly discharged in the winter months to compensate the lower capacity factors of RES.

Countries with a high base level of emissions like Germany, the UK, or Italy experience a quicker phase-out of fossil fuels than less emitting regions. The reason for that is the tight emission budget, forcing a rapid phase-out of fossil fuels in the early stages of the modeling period in order to achieve the 2° C goal. Figure 10 graphs the emissions over all regions. The red bars show the annual emissions, while the gray line is the sum of all emissions during the modeling period. First, the yearly emissions show a steady decline in total emissions, which by 2030 are more than halved compared to 2015 levels. This reduction is considerably lower than current emission reduction targets from the EU or the respective countries. Second, following this path, more than 90% of the total emissions are being produced until 2035, which showcases the high degree of decarbonization by then. Also interesting is the fact that this configuration would lead to a surpassing of the 1.5° C budget by 2020.

5.2 Emission pathways: business as usual and 1.5° C

In the business as usual (BAU) pathway, the model is not bound to any carbon budget. Rather, carbon prices from the IEA (2016) are assumed. This results in the model emissions not having to meet any constraint, enabling many regions to use more of their fossil fuels for a longer period. In contrast, the 1.5° C scenario allows for a total of 25.29 $GtCO_2$, which is not even half the amount of our base scenario. Hence, two substantially different pathways can be observed when analyzing and comparing them.

Figure 11 shows the development of electricity generation over the modeling period for both scenarios. It can be seen that in the case of the BAU scenario, hard coal and lignite remain in the electricity mix until 2050, being the cheapest option when it comes to conventional capacities. In addition, the total amount of generated electricity is notably lower than in the other scenarios, resulting from less electrification in the other sectors. In the 1.5°C scenario, on the other hand, an even faster phase-out of fossil generation technologies than in the base case can be observed. By 2040, no CO_2emitting technologies are being used, with hard coal and lignite being phased out as soon as 2025. Moreover, total generated electricity in 2050 is about 40% higher than in the BAU scenario and 20% higher when compared to the base scenario.

The difference between the scenarios becomes even more predominant when analyzing the outcomes for the high-temperature heating sector. Figure 12 showcases the respective results, again combined for the BAU and 1.5° C scenario. A high share of coal-based process heat can be seen in the former, which even increases during the first half of the modeling period and then remains flat. This indicates that the shift towards low-carbon technologies in the 2° C scenario was induced by the climate constraints. Consequently, in the stricter 1.5° C scenario, electricity plays an even more important part than in the base scenario. The final energy mix consists of electric furnaces and synthetic gas, since the valuable biomass potentials are needed in other sectors.

Lastly, the cumulative emissions of both scenarios are shown in Figures 13 and 14. On the one hand, the BAU scenario results in a total CO_2 output of 87.77 Gt, which is noticeably above the 2° C pathway limit. On the other hand, a yearly decrease of emissions can be observed, showing that for most sectors, renewables become increasingly competitive and are actually the lowest-cost solutions.[4] As explained earlier, the sector with the most difficulty of including RES is the high-temperature heating sector, where low-carbon alternatives are costly. Also, while emissions are steadily decreasing over the years, they still do not reach zero, meaning that a trajectory of at least 3° C is likely. For the 1.5° C scenario, GHG neutrality has to be achieved by 2035. As the budget sees an overshoot around 2025, negative emissions through biomass coupled with CCS are required to reduce the total amount of CO_2 in the atmosphere to the desired level.

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[4] i.e. emitting net zero emissions over the year.

Figure 11: Development of yearly power production in the BAU and 1.5° C pathway.

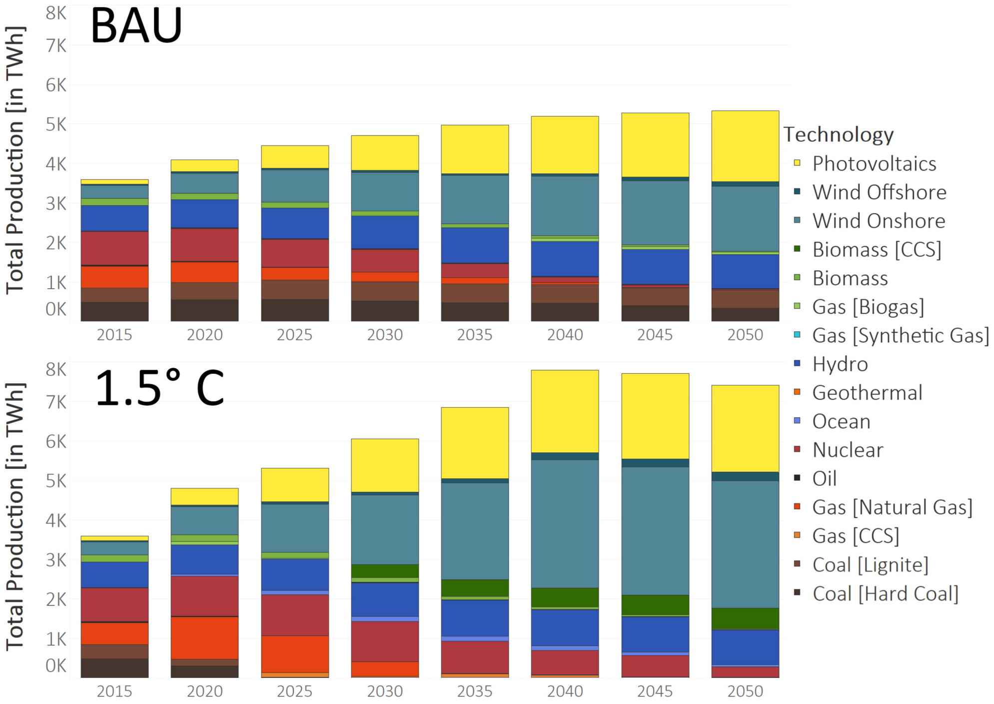


Figure 12: Development of yearly high-temperature heat production in the BAU and 1.5° C pathway.

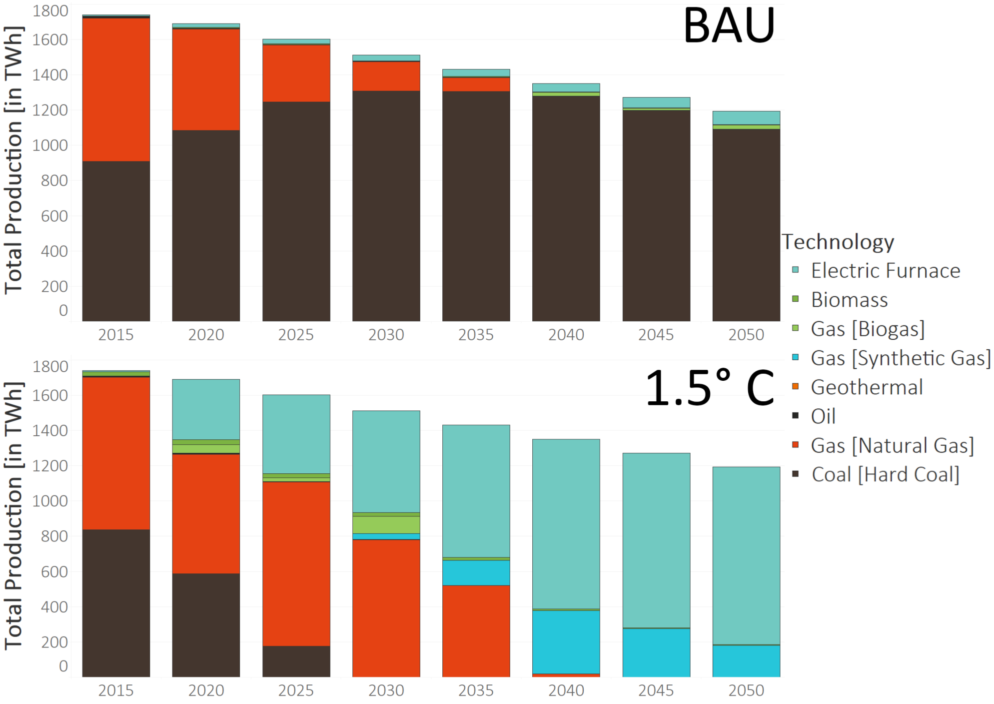


Figure 13: Yearly emissions (left) and cumulative CO_2 emissions (right) in the BAU pathway.

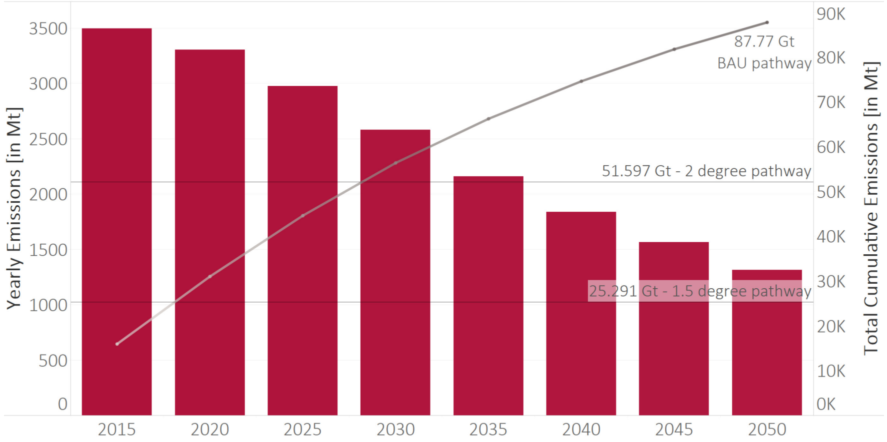
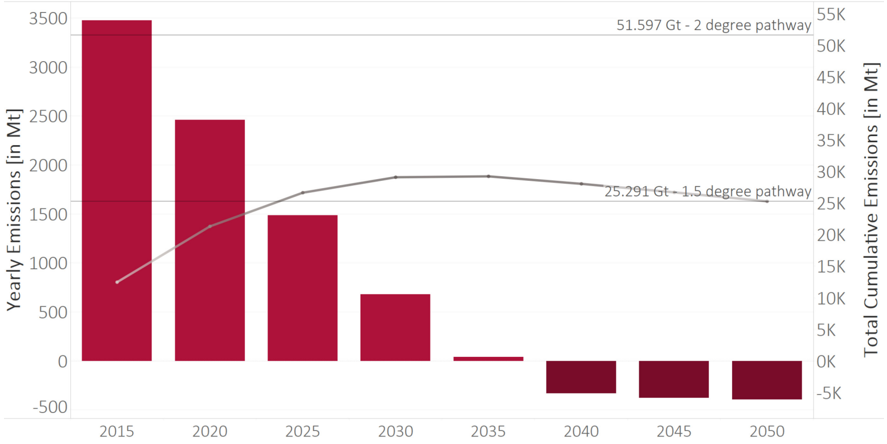


Figure 14: Yearly emissions (left) and cumulative CO_2 emissions (right) in the 1.5° C pathway.



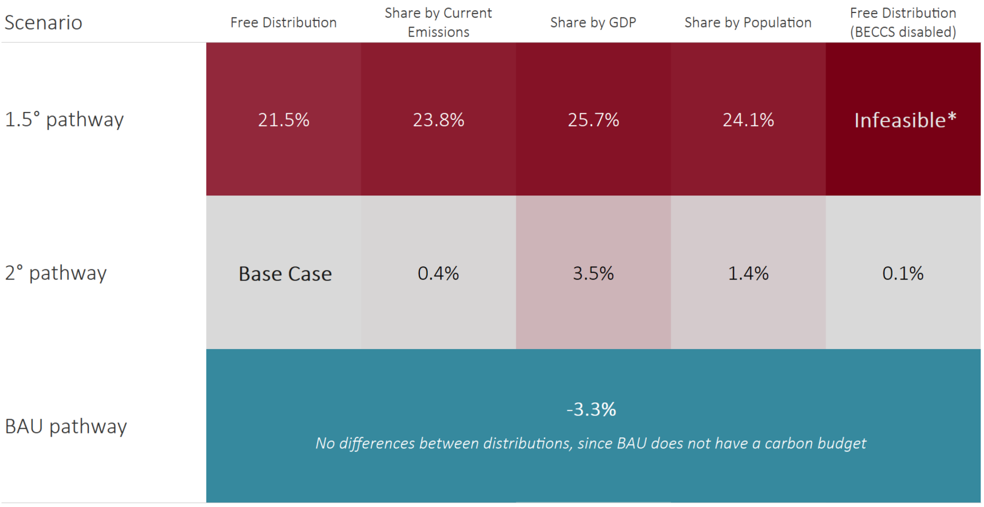
5.3 Comparison of emission pathways

The model results show that for each emission pathway, a cost-optimal solution for keeping the set emission targets can be found. This also holds true for a sensitivity analysis, where BECCS has been disabled, except for the 1.5° C scenario, where a (technically) feasible solution cannot be found based on the assumed constraints. Figure 15 shows a comparison of total costs, relative to the base case (2° C pathway, free distribution of emissions).

As expected, the 1.5° C pathway nets the highest total costs, at least 21.5% higher than those of the 2° C pathway. The BAU pathway is cheaper overall, albeit only by about 3.3% than the base scenario. When it comes to distribution scenarios, the planner-perspective “Free Distribution” scenario yields the lowest overall costs, since it distributed emissions solely on a cost optimization basis. When introducing region-specific limits of emissions, an overall increase in system costs can be observed, except for the BAU pathway, where the overall emission constraint is relaxed enough so that distribution only plays a minor role.

It is important to note that not all negative externalities (such as health or environmental costs) are represented in these values and would likely shift the costs in favor of the low-carbon pathways. Studies show that the possible damages heavily outweigh the abatement costs (Stern, 2007).

Figure 15: Cost comparison of all emission pathways and distribution scenarios. Relative change in total costs compared to the 2° C, free distribution, scenario.



Scenario	Free Distribution	Share by Current Emissions	Share by GDP	Share by Population	Free Distribution (BECCS disabled)
1.5° pathway	21.5%	23.8%	25.7%	24.1%	Infeasible*
2° pathway	Base Case	0.4%	3.5%	1.4%	0.1%
BAU pathway	-3.3% *No differences between distributions, since BAU does not have a carbon budget*				

Notes: A pathway staying true to 1.5° C without the usage of negative emissions technologies can only be achieved by using extreme measures, such as sufficiency, reduced (maybe negative) demand growth, and drastic changes to the energy supply within a short timeframe.

Results show that apart from the (economically optimal) *Free Distribution* of CO_2 within the EU, a distribution share based on current emissions is the least-cost option. In both the 1.5° C as well as the 1.5° C pathways, its deviation from the optimum is at its lowest point. A distribution based on GDP, however, sees an increase of about 3.5% in total system costs for the 2° C pathway, and about 4.2% for the 1.5° C pathway.

It needs to be highlighted that the feasibility of achieving the 1.5° C target is coupled to the availability of net-negative emission technologies (here bio-energy with carbon capture and storage (BECCS)). This is a highly controversial topic, as net-negative emission technologies, e.g. relying on carbon- capture-and-storage are often seen as an easy way to achieve climate goals in energy system models but yet remain to be proven (Hirschhausen et al., 2012). However, given the very tight carbon budget and the current yearly emissions of Europe, an overshoot of the carbon budget for 1.5° C seems almost unavoidable and can only be coped with via negative emissions in the model, showcasing that for the achievement of such strict targets, one would not only need a net-zero, but instead a net-negative emission energy system from 2040 onwards.

On the other hand, it can be demonstrated that CCS is actually no cost-efficient alternative when emission targets are not as strict. The removal of BECCS from the model yields little to no cost difference for both the 2° C and BAU pathways, as BECCS plays almost no role in said model solutions. Especially in later years, RES are cheaper than fossil fuels in nearly all sectors. This fact becomes especially prevalent when comparing the BAU and 2°C pathways, where the achievement of climate targets comes at comparably little costs, while reducing total emissions by more than 30%.

5.4 Discussion

5.4.1 Fossil fuel prices

When taking a look at the possible transition towards renewable energies in an energy system, one has to pay close attention to the underlying prices for fossil fuels. Determining the future prices of fossil fuels is a difficult task, with only few reliable sources available. The International Energy Agency (IEA), for example, predicts fuel prices in line with their scenarios. The problem with this is that the model results are still based on large shares of fossil energy carriers, often in combination with CCS. This is where the issue of the “green paradox” arises (Sinn, 2008). Since we estimate large shares of renewables coming into the system, the demand for fossil fuels would fall drastically, and thus their price would have to decline as well. This would in turn lead to a slower transformation towards renewables, as cheap fuel prices could get fossil fuel based generation to become competitive once again. Current assumptions of fossil fuels priced as a finite resource (with thus constantly increasing costs) might have to be revised and updated. This task will become increasingly important in the future, as these price assumptions (together with potential carbon pricing) drive model-based results, and thus, decisions.

Although important to keep in mind, these issues are most adequately dealt with using scenario and sensitivity analyses. Multiple sensitivities for fossil fuel prices have been calculated and examined to test the robustness of the results, although there might be opportunities for future research to include such simulations into the scope of the model.

5.4.2 Solar PV potentials

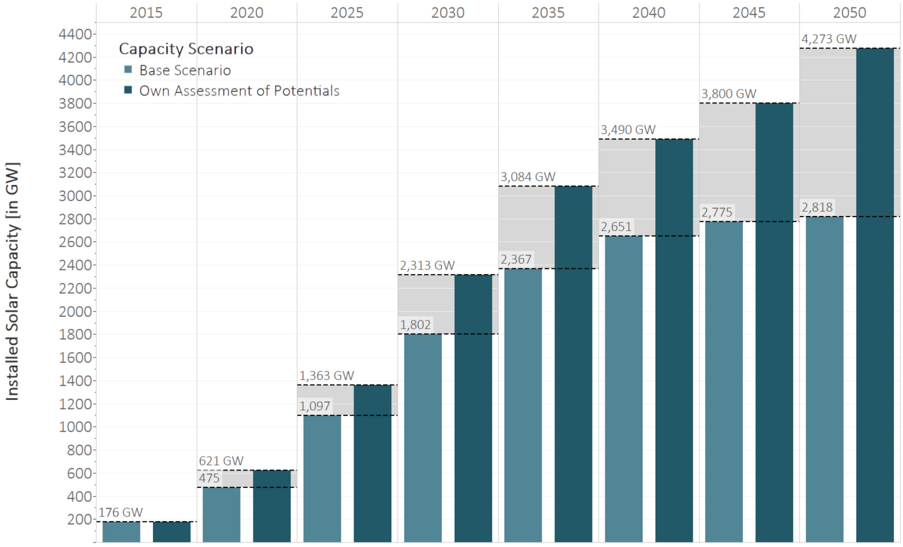
As with prices, the theoretical potentials for renewable supply technologies strongly drive model results. Assumptions concerning both the amount of available land and the definition of such are a heated topic in both science and policy (as seen in Clack et al. (2017); Jacobson et al. (2017)). The decision about these values directly influences the modeling constraints, and can therefore steer results in certain directions.

The values chosen for our model runs (see section 5.4.2) concerning solar PV potentials are quickly exhausted, with some regions reaching the maximal values as soon as 2030. Given other results in literature (e.g. Ram et al. (2017)), this seems rather early. As a comparison, an own assessment of solar potentials has been conducted, using solar radiation data and assuming a usable amount of land of 4% across all regions.

The results (depicted in Figure 16) show that the possible solar potential heavily influences the results for a transition towards renewables in Europe. Especially in the sunnier regions in the south of Europe, vastly larger amounts of solar capacities are constructed and shift both the resulting production mix, as well as the grid structure and expansion.

This shows that great caution has to be placed on assumptions about suitable land, maximum land usage, and thus, consequently, expansion potentials. In future work, even more effort should be placed in obtaining reasonable capacity potentials for RES, as well as sensitivity analyses. Especially crucial transition technologies, such as solar PV, should be observed carefully in such long-term decarbonization scenarios.

Figure 16: Development of installed solar capacities in both reference case and alternative assessment.



5.4.3 Further points of discussion

In addtion to the aforementioned points, other aspects can not be displayed by the model but deserve attention anyway. An example would be the different barriers which renewable energy infrastructure face in different countries, from both a political side (e.g. onshore wind limitations in Bavaria, Germany),[5] but also including social and psychological effects such as the not-in-my-back-yard phenomenon (Wolsink, 2012). We do not consider these effects as they are difficult to impossible to quantify, yet they have to be kept in mind when developing policies.

As mentioned in Burandt et al. (2018), policies which are currently already in place are being considered (e.g. nuclear phase-out in Germany). However, some policies promoting renewable energies but also subsidies for fossil fuels or capacity markets are not displayed. The model does not determine policies endogenously, but an update on more recent political design can be applied in further research.

Moreover, it has to be kept in mind that political decisions are not only based on least cost scenarios but also include other elements (e.g., employment, health, and environmental effects to name a few). Some of them could be monetized and subsequently be accounted for in the date, but they mostly require a different modeling approach. With advances in computational capacity, future work and research can and should be placed on the topic of including these aspects in our model calculations with enough detail.

6. CONCLUSION

If the concentration of GHGs is not reduced significantly within the near future, irreversible and severe consequences for humans and natural systems are the consequence (McMichael et al., 2006). One of the biggest contributors of GHG emissions is the energy sector, accounting for

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[5] Online reference: http://www.gesetze-bayern.de/Content/Document/BayBO.

more than two thirds of the global emissions (IEA, 2016). Therefore, various challenges arise for different countries when it comes to decarbonizing their energy systems. Especially highly developed countries and regions, such as the EU have an obligation to play a leading role in the transition towards renewable energy sources.

In this paper, possible decarbonization pathways, using varying assumptions for carbon constraints and distributions among the chosen model regions, were analyzed. For the analysis, the Global Energy System Model (GENeSYS-MOD) has been used, minimizing total system costs for the sectors power, heat, and transportation. The framework has been expanded with various new functionalities and improvements, such as an upgrade to the trading system with respect to power trade, or overall performance optimization. Additionally, a new and improved data set, introducing new technologies (especially in the transportation sector) and featuring 16 time slices,[6] has been added to GENeSYS-MOD v2.0. Europe is modeled in a total of 17 regions, with model calculations optimizing the pathway from 2015 to 2050 in five-year steps.

Three different pathways have been considered: a pathway that limits global warming to 2° Celsius (C), a 1.5° C pathway, and a business as usual (BAU) pathway. But while the overall emission trajectory is relevant on a global scale, the distribution of these emission budgets onto the European countries has great importance, especially considering possible policy implications. Thus, a total of four distribution methods for the set carbon budget have been examined: free distribution,[7] share by GDP, share by population, and share by current emissions.[8] The results indicate that even ambitious climate targets can be met, both technically and economically. All modeled pathways and distribution scenarios were solvable, but the 1.5° C pathway faces serious cost and technology issues, being heavily dependent of the availability of BECCS (or any other negative emissions technology for that matter). Given the extremely low carbon budget and current yearly European emissions, an overshoot is to be expected within the next few years, which can only be covered by achieving not only net-zero, but net-negative emissions. It can be shown that reaching a climate target of 2° C only nets a cost increase of about 3.3%, while reducing total emissions by more than 42% compared to the BAU case. Staying below 1.5° C causes total system costs to go up by at least 21.5%, but reducing emissions by another 51%. This does, however, not account for negative externalities, such as health, environmental, or climate costs, which could severely shift the ratios towards the low-carbon scenarios.

No matter which distribution is chosen, the model results show that meeting ambitious climate targets requires widespread effort and possibly policy instruments in the near future. While much of the renewable transformation is market-driven (as can be seen in the BAU scenario), set goals of well below 2° C can only be achieved, if carbon constraints are met - which requires policy action. However, the noteworthy main finding of the study is that even with a low cost increase of 3.3%, emissions can be drastically reduced (by over 42% compared to the BAU pathway) which allows for a compliance to a 2° C target.

As always with quantitative, model-based research, certain aspects of the real world can only be included in a simplified version into the model. While the extension of the amount of time slices greatly improves the temporal setting of the model, there are still limitations to the amount of variability that can be observed with the setting. Further research should take a closer look at real-life implications of the obtained model results, such as the stranded asset problem that could arise, given

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[6] Instead of the previous six time slices.

[7] Meaning endogenous optimization on a cost-minimizing basis, calculated by the model.

[8] Considering current emissions and installed fossil capacities, more emission shares are given to countries that rely more on these fossil capacities and will thus have a more difficult time transitioning to RES in the shortterm.

the fast phase-out of fossil generation capacities, especially in Germany and several Eastern-European countries. Given the original world-wide setting of the utilized framework GENeSYS-MOD, larger scale research, including a more detailed version of Europe into the global framework, is also something to consider. Some effort should also be placed into more model-improvements, such as adding more load-balancing options, for example in the form of reworked storages, or the implementation of BEV as electricity storage into the model.

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APPENDIX

Appendix A: Additional Data

A1 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
British Isles	212.2	268.8	364.6	845.6
Total	1865.2	2774.2	1632.2	6271.6

Source: Gerbaulet and Lorenz (2017).

A2 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: IEA (2016).

A3 Capital expenditures of renewable power production technologies in €/kW.

	2015	2020	2025	2030	2035	2040	2045	2050
Solar								
PV Roof Commercial	1360	907	737	623	542	484	437	397
PV Roof Residential	1360	1169	966	826	725	650	589	537
PV Utility	1000	580	466	390	337	300	270	246
CSP	3514	3188	2964	2740	2506	2374	2145	2028
Wind								
Offshore Shallow	2975	2241	1870	1646	1530	1454	1395	1353
Offshore Transitional	3500	2637	2200	1936	1800	1710	1642	1592
Offshore Deep	4025	3032	2530	2226	2070	1967	1888	1831
Onshore	1250	1150	1060	1000	965	940	915	900
Hydro								
Large	2200	2200	2200	2200	2200	2200	2200	2200
Ocean	9890	5095	4443	3790	3083	2375	2238	2100
Others								
Geothermal	5250	4970	4720	4470	4245	4020	3815	3610
Biomass	2890	2620	2495	2370	2260	2150	2050	1950

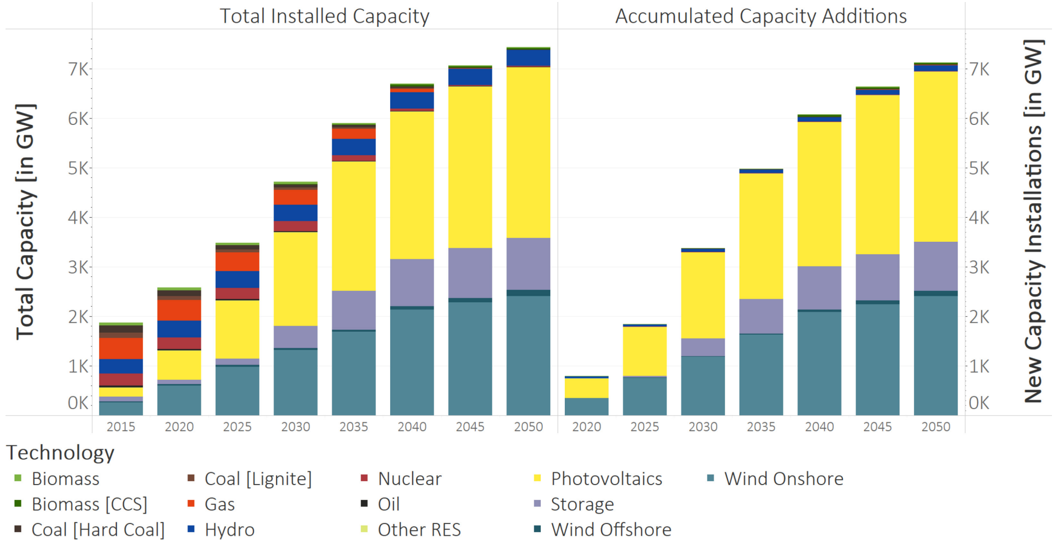
Source: Gulagi et al. (2017), Carlsson et al. (2014), Gerbaulet and Lorenz (2017), and Ram et al. (2017).

A4 Own assessment of utility-scale solar potentials in Europe.

[GW]	Potential per Category (avg / opt / inf)	Total Potential
Austria	56.59	169.77
Baltic States	92.58	277.74
Belgium & Luxembourg	19.17	57.51
Czech Republic	44.75	134.25
Denmark	18.67	56.01
France	394.66	1183.98
Germany	61.53	184.59
British Isles	121.87	365.61
Italy	237.96	713.88
Netherlands	21.26	63.78
Poland	177.39	532.17
Portugal & Spain	591.59	1774.77
Scandinavia	509.49	1528.47
South-East Europe	326.07	978.21
Switzerland	25.09	75.27
Total	2698.67	8096.01

A5 Total installed capacity and new capacity additions.

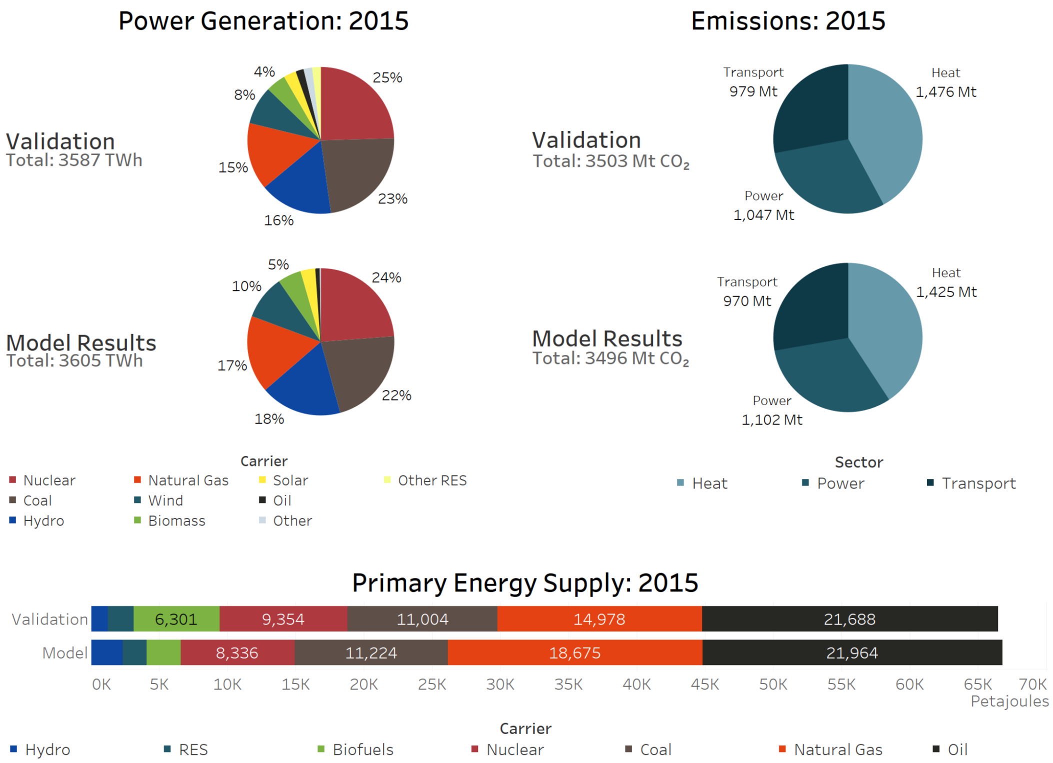
Figure 17: Total installed capacities (left) and new capacity additions (right) for the base scenario [in GW].



APPENDIX B: MODEL VALIDATION

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 18 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 18: Comparison of 2015 model results vs. historical numbers. Own calculations, 2015 data based on IEA (2018a); Statistical Office of the Republic of Serbia (2017); Swissgrid (2015); IEA (2018b); OECD (2017), Statistics Norway*.



* Online reference: https://www.ssb.no/en/energi-og-industri/statistikker/elektrisitet/aar

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 (some of them highlighted in section 5.4) to ensure proper functionality and behavior of the model. All tests showed a predicted and/or explainable behavior of the model.