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Emission pathways towards a low-carbon energy system for Europe: A model-based analysis of decarbonization scenarios

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Emission Pathways Towards a Low-Carbon Energy System for Europe

A Model-Based Analysis of Decarbonization Scenarios

Karlo Hainsch¹, Thorsten Burandt^{1,2}, Claudia Kemfert^{1,3,4}, Konstantin Löffler^{1,2,*}, Pao-Yu Oei^{1,2},
and Christian von Hirschhausen^{1,2}

Abstract

The aim of this paper is to showcase different decarbonization pathways for Germany and Europe with varying Carbon dioxide (CO₂) constraints until 2050. The Global Energy System Model (GENeSYS-MOD) framework, a linear mathematical optimization model, is used to compute low-carbon scenarios for Europe as a whole, as well as 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 climate targets is chosen. In the 2° pathway, the power and low-temperature heat sectors are mostly decarbonized by 2035, with the other sectors following. Wind power is the most important energy source in Europe by 2050, followed by solar energy and hydro power. The heating sector is dominated by biogas and heat pumps, while electric vehicles emerge in the transportation sector in the later periods. Differences in renewable potentials lead to different developments in the regions, e.g., converting Germany from a net exporter of electricity into an importing country by 2050. In the 1.5° pathway, not all calculations are feasible, showcasing that especially countries like Poland or the Balkan region that heavily rely on fossil fuels will face difficulties transitioning away from their current generation capacities. It can, however, 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

JEL codes: C61, Q4, L9

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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 2016). The most important greenhouse gas is CO₂, which is responsible for more than 80% of the emissions in the energy sector (Foster and Bedrosyan 2014). 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. Yet, no exact configuration of the energy system is defined, and countries have to promote their own policies to reach the goals.

In recent years, the focus was heavily set on decarbonizing the electricity sector. However, in a fully decarbonized energy system, the heating and transportation sector deserve just as much, if not more attention, due to the challenges of phasing out fossil fuels in these areas. A high degree of electrification in these sectors is predicted in future scenarios, which implicitly affects the power sector.

The power sector is by far the most wide-spread sector of choice when it comes to analyzing energy system transitions towards less GHG emissions. Some studies focus solely on the electricity sector on a European scale and analyze impacts of high renewable penetration (Gerbaulet et al. 2017; Scholz 2012; PwC 2011; Czisch 2007; Plessmann and Blechinger 2016). Gerbaulet et al. (2017) analyze different scenarios for the European electricity sector with high amounts of renewables, showcasing that neither high shares of carbon capture and storage (CCS) nor nuclear power are necessary for such a system to be feasible. Scholz (2012) shows that most European countries will be able to cover their domestic power demand on their own, with countries like Belgium or Luxembourg relying on grid interconnections with other countries. Czisch (2007) comes to similar results, concluding that given enough grid capabilities between European and North African countries, renewable electricity could be produced and distributed at costs similar to today's.

In addition to production and distribution, electricity storages and their incorporation into the power sector are the focus of many other studies. While all of the above-described authors mention storages as an element of future energy systems, others take a closer look. In general, a positive correlation between high shares of renewables and storage capacities can be found across the literature. Schill and Zerrahn (2017) highlight in addition that the relevance of power storages is even higher, if other flexibility

options are less developed. Bussar et al. (2015) suggest storage capacities of 804,300 Gigawatt hours (GWh) in 2050, most of which consist of gas storages. Also, a negative correlation between storage and trade capacities can be observed, showcasing the power grid as another form of storage. In contrast, Rasmussen, Andresen, and Greiner (2012) find that, without additional balancing, storage capacities of 320 Terawatt hours (TWh) are required. However, they acknowledge that hydrogen storages would increase this number substantially.

On a global scale, Jacobson et al. (2017a) published one of the most comprehensive studies lately, showcasing 100% renewable energy roadmaps for 139 countries of the world. Electricity is produced by wind, water, and solar technologies and a significantly more aggressive pathway than what the Paris agreement calls for is projected. However, his methodology and results of a different paper were origin to a controversy between researchers (Clack et al. 2017; Jacobson et al. 2017b). This not only showcases the prevalence of the topic, but it also highlights the various paradigms within the field.

2 Model and Data

2.1 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. (2017b) and (Burandt, Löffler, and Hainsch 2018).

In essence, GENeSYS-MOD can be illustrated as a flow-based 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. Figure 1 gives a general overview of the different *Technologies* and the connections between them.

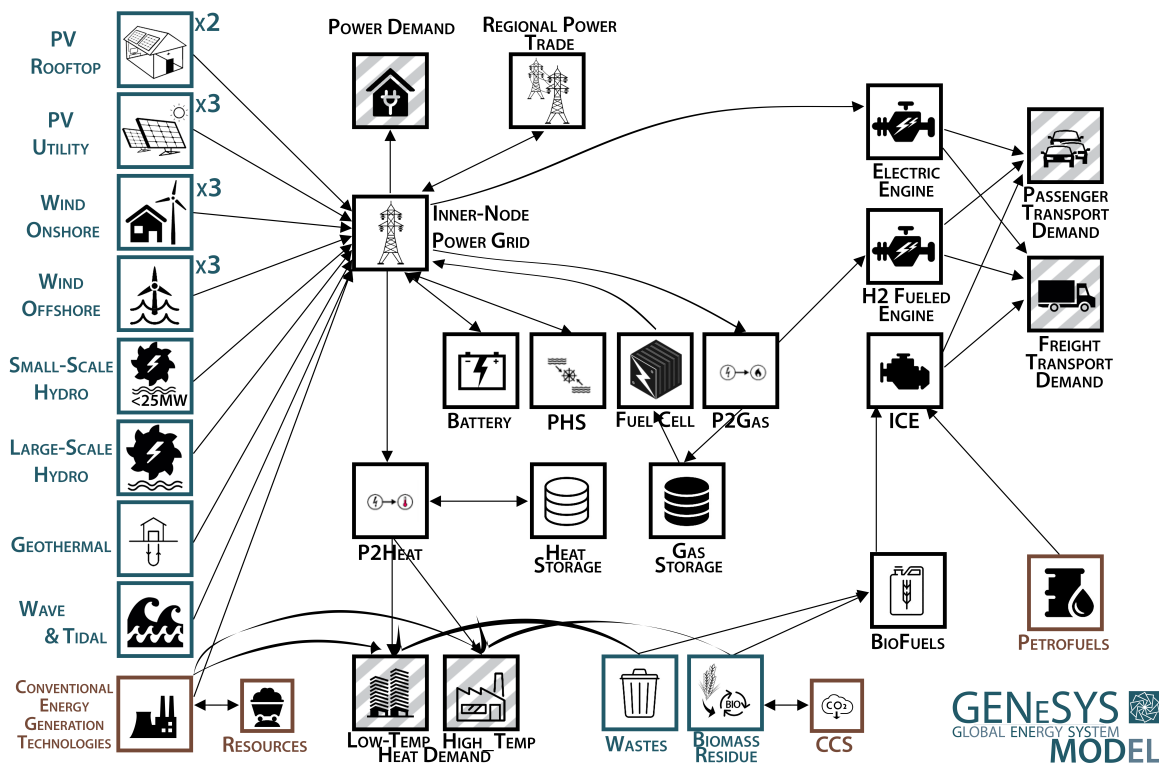


Figure 1: Model structure of GENeSYS-MOD v2.0.

Source: Own illustration.

GENeSYS-MOD v2.0 offers a fully updated data set for all global parameters, such as fuel prices, general cost assumptions, and emissions data. 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, as shown in Figure 2.

A detailed overview of all changes and additions in GENeSYS-MOD v2.0, both for model and data, can be found in the accompanying DIW Data Documentation 94 (Burandt, Löffler, and Hainsch 2018).

2.2 Model setup and data

2.2.1 Spatial resolution and grid data

Since the focus of this work is the European region, a corresponding geographical resolution had to be found. Similar to the case study for India conducted with the first version of GENeSYS-MOD (see Löffler

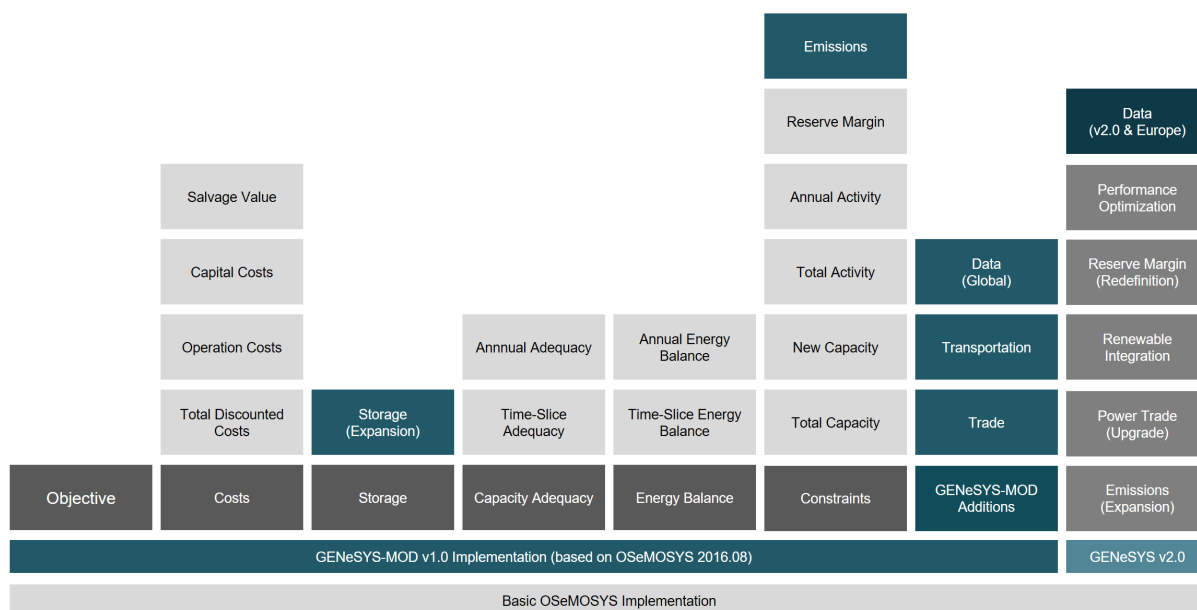


Figure 2: Block structure of GENeSYS-MOD v2.0.

Source: Own illustration, based on Howells et al. (2011).

et al. (2017a)), the broad world region "Europe" was split up into multiple smaller regions to fit the scope of the study.

The European energy system is represented by 17 nodes. A focus has been placed on Germany and its central role, both geographically and politically. Hence, Germany and all its neighboring countries are modeled as single regions (with Luxembourg being the exception), whereas the resolution gets broader when moving to the edges of the European region. There, multiple countries are aggregated into one region, based on matching regional potentials and conditions. The chosen regional disaggregation of Europe with 17 nodes in total leads to a stylized version of the European electricity grid. The resulting grid structure with its possible connections between nodes can be found in figure 3. Grid capacities for Europe have been taken from Gerbaulet and Lorenz (2017).

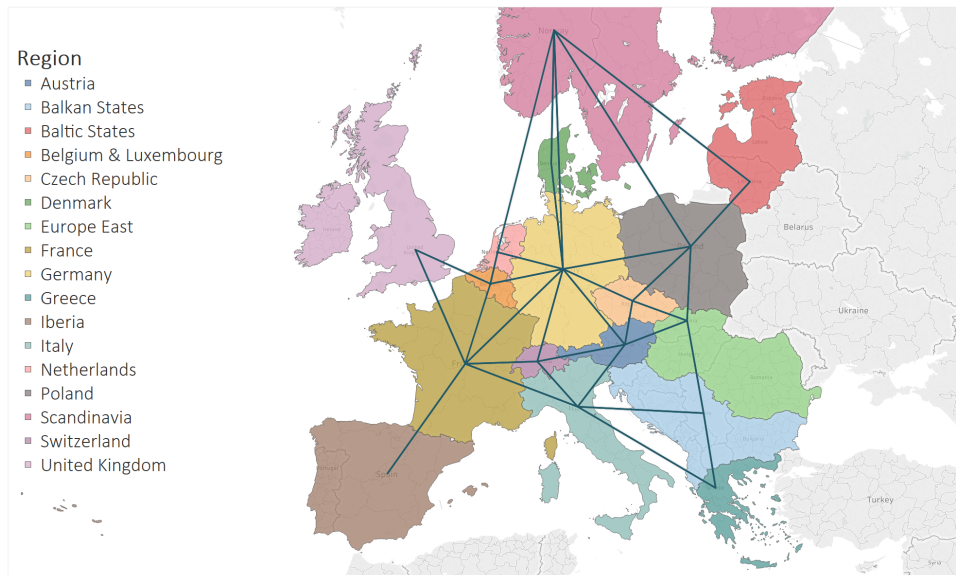


Figure 3: Grid structure and node set-up for Europe.

Source: Own illustration.

2.2.2 Temporal resolution

This temporal disaggregation has been revised and updated, now featuring four quarters of a year, and four daily time brackets, to a total of 16 time slices per year. A similar approach can be found in Welsch et al. (2012), where they show that an energy system model using an enhanced version of Open Source Energy Modelling System (OSeMOSYS), utilizing 16 time slices, can achieve almost the same results as a full hourly dispatch model.

For each quarter, the daily time brackets which determine the time slices are slightly different. This approach was chosen to facilitate a better match of solar load profiles, since sun availability vastly differs between seasons. Each day is split up into a) morning, b) peak, c) afternoon, and d) night. The daily sun-hours for Germany (taken as representative for Europe, since its central geographical location gives a good mean value for the region) have been used as outlines for the daily time brackets. Table 1 shows the chosen hours per day for each time slice.

Table 1: Hourly assignment of daily time brackets.

[hours:minutes]	Q1	Q2	Q3	Q4
Morning	07:30 - 09:00	05:00 - 08:00	06:00 - 08:00	07:30 - 11:00
Peak	09:00 - 13:00	08:00 - 16:00	08:00 - 15:00	11:00 - 13:30
Afternoon	13:00 - 17:00	16:00 - 21:00	15:00 - 20:30	13:30 - 16:00
Night	17:00 - 07:30	21:00 - 05:00	20:30 - 06:00	16:00 - 07:30

Source: Based on average sun hours in Germany for the year 2015.

2.2.3 Technology representation in the model

The list of technologies has been taken from the prior model version and has then been revised. Some technologies did receive updates in their implementation, others were added, and some have been removed. Heating technologies no longer have centralized and decentralized counterparts. This simplification is due to our rough regional disaggregation, which does not profit from such a distinct analysis of heating technologies. Instead, centralized and decentralized heating technologies for each type (e.g., low-temperature gas heating) have been combined into one unified technology. A total of 15 centralized heating technologies (including the area technologies) have been omitted from the model.

2.2.4 Potentials of renewable energy sources

The total potential for renewable technologies is often disputed, even among experts, with heavily varying values. The choice of maximum land usage, as well as the underlying weather data (e.g., choice of the base year), strongly impact these numbers and quickly lead to an over- or underestimation of actually available potentials. The renewable potential data for the European region presented in this study stem from the model dynamic Electricity Model (dynELMOD) (Gerbaulet and Lorenz 2017), which, in turn, is based on an expert assessment by the Potsdam Institute for Climate Impact Research.

2.2.5 Capacity factors

Capacity factors for renewable generation have been taken from Pfenninger and Staffell (2016), given as an hourly time series for the year 2014. For each region, multiple samples have been taken, placed into a category, and then taken as average for each region, category and time slice. Solar photovoltaic (PV) and onshore wind are divided up into the three categories a) optimal, b) average, and c) inferior, while offshore wind has been categorized as a) shallow, b) transitional, and c) deep.⁵ The categories of PV and onshore wind only differ in the capacity factors whereas the particular types of offshore wind parks additionally have different capital and Operation and maintenance (O&M) costs. Therefore, we decided to use another kind of categorization for offshore wind.

2.2.6 Cost data

For utility-scale PV and onshore wind, expenses have been assumed to be the same across all three categories. For offshore wind, the placement of turbines influences the resulting construction costs a lot more (e.g., near-shore vs. deep-water placement) with cost estimate ranges of up to more than double

⁵The regional potential has been assumed to be evenly distributed across the categories, as per Gerbaulet and Lorenz (2017)

the price. Hence, offshore wind has its capital costs given separately for each category. The capital costs for fossil-based plants are assumed to be constant over the years, while renewables experience decreasing costs over the modeled time frame. Fixed costs are assumed as a percentage of capital costs, as in GENeSYS-MOD v1.0. Variable costs for renewable technologies are still considered to be zero.

The prices for fossil fuels in the second version of GENeSYS-MOD have been split up into local and global prices. These global prices are tied to the global market price of each fuel and have been updated from the 2015 version of the World Energy Outlook of the International Energy Agency (IEA) to the 2016 version (IEA 2016). This means a drastic reduction in the price forecast, especially for oil (where the difference results in an almost halved future oil price compared to the forecast from 2015 (IEA 2015)).

Because of the regionally dependent availability and usage of lignite, local prices have been applied, where available.⁶ For hard coal, natural gas, and crude oil, it has been assumed that local production is 5% cheaper than the global market price.⁷

2.2.7 Emissions budget

The emissions budget available for the model has been revalidated in GENeSYS-MOD v2.0. Additionally, a regional, European, limit was obtained from the given global emission budgets that are provided in the most recent literature.

In the modeled scenarios, keeping the temperature well below 2° Celsius is the primary goal, and the corresponding available CO₂ budgets provided by the IPCC (2014) are used. For the calculation of the total CO₂ budget for Europe, data provided by the Stockholm Environment Institute was used (Kartha 2013). This discussion briefly assesses the pathways that were released in the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC 2014) and further elaborates different budgets for the various types of greenhouse gases. Accordingly, a global CO₂ budget of 890 GtCO₂ for the years 2012 to 2050 is accessible. Based on the yearly CO₂ emissions of around 36 Gt, as found in the Global Carbon Atlas,⁸ the global budget is reduced to 782 GtCO₂ for the modeled base year 2015. Because GENeSYS-MOD does not include exogenous CO₂ emissions from specific industrial branches (e.g., cement manufacturing), we reduce the limit by 2 GtCO₂ for all years from 2015 to 2050 (Boden,

⁶The value for Portugal & Spain is the average of the other values, since no reliable source for a specific value was found.

⁷Only countries that currently mine hard coal are assumed to have this price advantage. Countries that have reserves, but do not currently mine hard coal, have their price increased by 5% compared to the market price to avoid the unrealistic domestic production in such cases.

⁸See <http://www.globalcarbonatlas.org/en/CO2-emissions> for further information. Data is based on Boden, Andres, and Marland (2017), UNFCCC (2017), and BP (2017).

Andres, and Marland 2017; UNFCCC 2017; BP 2017). This leaves a final global CO₂ budget of 712 GtCO₂ available until 2050.

2.2.8 CO₂ storage potential

The available CO₂ storage potentials for CCS are given on a regional basis. As the current political framework prohibits the transport of pollutants and waste, CO₂ must be captured within each country. Thus, countries without any CO₂ storage capacities cannot utilize CCS technologies. Based on the calculations and data available from Oei, Herold, and Mendelevitch (2014), only offshore storage capacities in aquifers, and depleted gas fields are included.

2.2.9 Carbon pricing

While the global implementation of GENeSYS-MOD v1.0 (Löffler et al. 2017b) opted for a strict emissions budget and a 100% renewable energy target, the constraint of a fixed renewable energy sources (RES) target for 2050 has been lifted. Before, no carbon price was set, since the much stricter target for renewable energies and perfect foresight of the model showed that the difference in terms of model results was negligible (Burandt et al. 2016). With the removal of said limitations, the introduction of a carbon price to the model was necessary. The carbon prices for Europe have been taken from the (IEA 2016).

3 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 CO₂ 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 the distributing the remaining available budgets and the country-specific allocations, 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 CO₂ limit and the fairest distribution for the European region.

The WBGU (2009) promotes an emission per-capita approach of distributing the CO₂ 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 CO₂ emissions, 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 Council on Global Change (WGBU), we look at scenarios within the "responsibility for the future" approach.

To define these distributions, several national key indicators were used. Considering the possible combinations of these scenario types, a total of 12 different scenarios is set up.

The following three emission pathway scenarios were implemented:

- **1.5°:** The model gets a strict CO₂ limit of 25.29 GtCO₂ for Europe. Considering the current CO₂ emissions of around 5.6 GtCO₂, 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° Celsius is possible.
- **2°:** The scenario of keeping the temperature below 2° Celsius is used to compare the different decarbonization pathways of the modeled European regions. It has a carbon budget of 51.60 GtCO₂. This emission pathway, coupled with a free, distribution of the European CO₂ limit is further referenced as the base scenario.
- **BAU:** When using the current yearly emissions and possible efficiency additions of 30% as a base-line for the future years, we get a total budget 137.39 GtCO₂. This scenario serves to analyze if a decarbonization would still happen, even with a relaxed emissions budget.

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

- **Regional Limit / Free Distribution:** No fixed share of the European CO₂ 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.

For distributing the emissions to our model regions, data available from The World Bank (2017) was used. Using data and assumptions, the regional shares, as seen in Figure 4, were calculated.

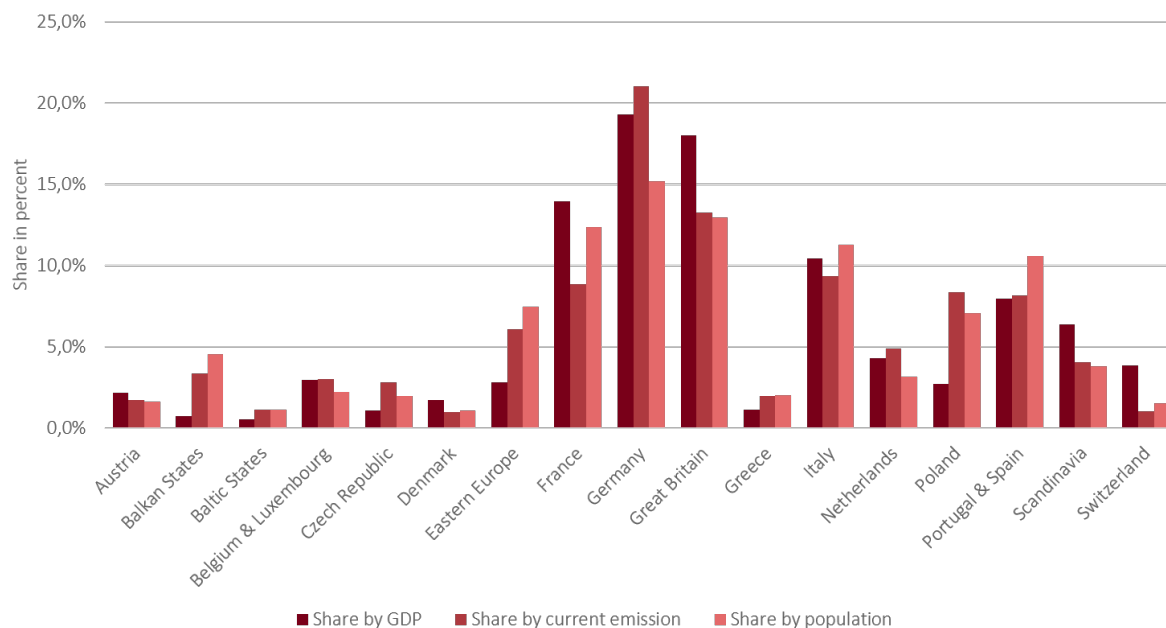


Figure 4: Calculated emission shares in the different scenarios.

Source: Own illustration, based on The World Bank (2017).

4 Results and discussion

4.1 Emission pathway: 2 degrees

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 5 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 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 CO₂-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 opposing coal technologies. The early growth is tied to a substantial rise in production, which originates from demand increases and the beginning of the electrification of the other sectors. By 2040, both natural gas and coal are almost nonexistent in the power sector. Nuclear energy is the only conventional generation technology that survives until 2050, although its share by then is substantially lower than today.

As for renewable energy sources, onshore wind, PV, and hydro power are the predominant technologies. 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.

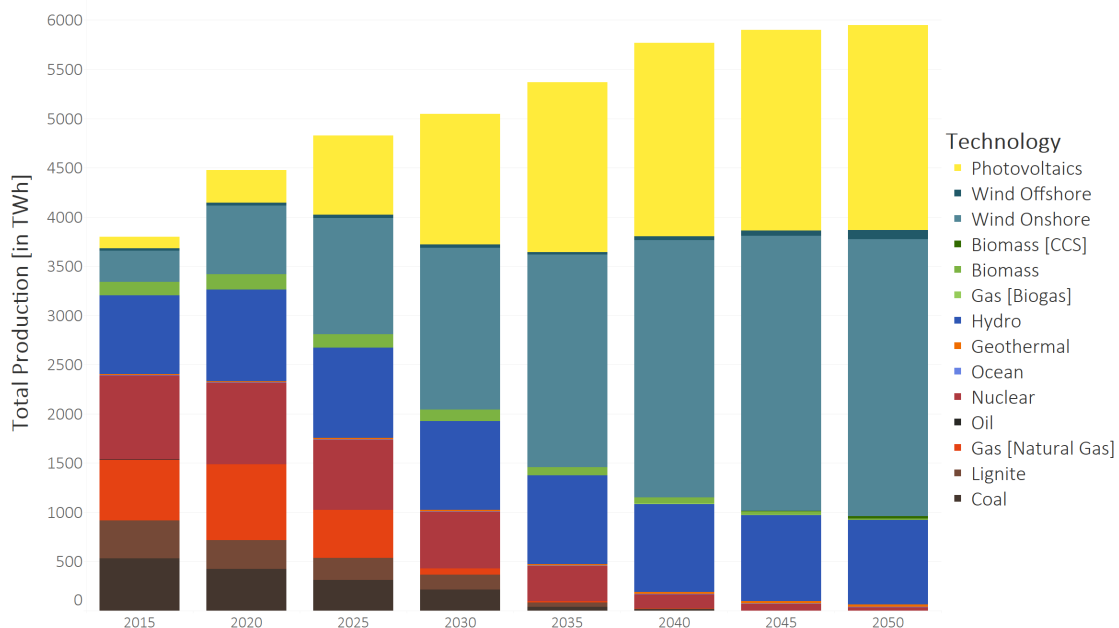


Figure 5: Development of power production in the base scenario.

Source: Own illustration.

Comparing the power production of the various regions, different developments can be observed, as illustrated in figure 6. 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. Great Britain, 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, Great Britain adds 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.

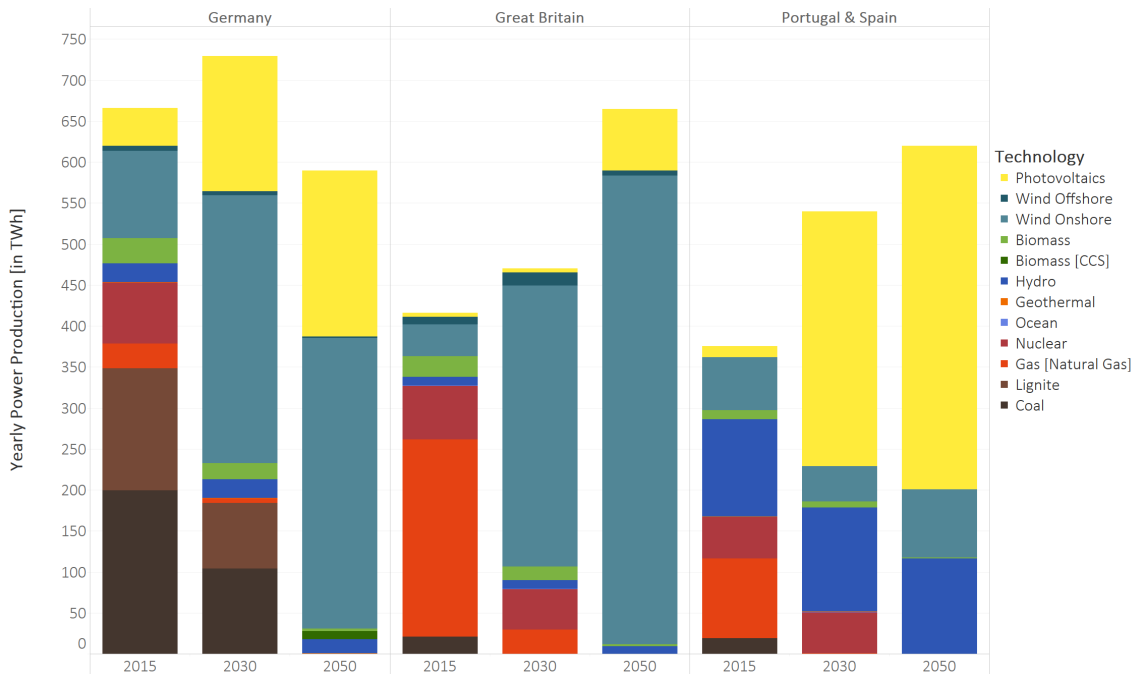


Figure 6: Power production profiles for Germany, Great Britain, and Portugal and Spain in the years 2015, 2030, and 2050 in the base scenario.

Source: Own illustration.

The overall electricity production is increasing by about 44%, 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 additional amounts of power becomes to light. In figure 7 the pathway of the low-temperature heating energy is shown. As before, conventional technologies are grouped in the bottom of the figure, while new, "green", 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. Coal, while being less significant than natural gas, does not show such a drastic decrease in importance. Still, by 2040, even coal is phased out of the low-temperature heating sector.

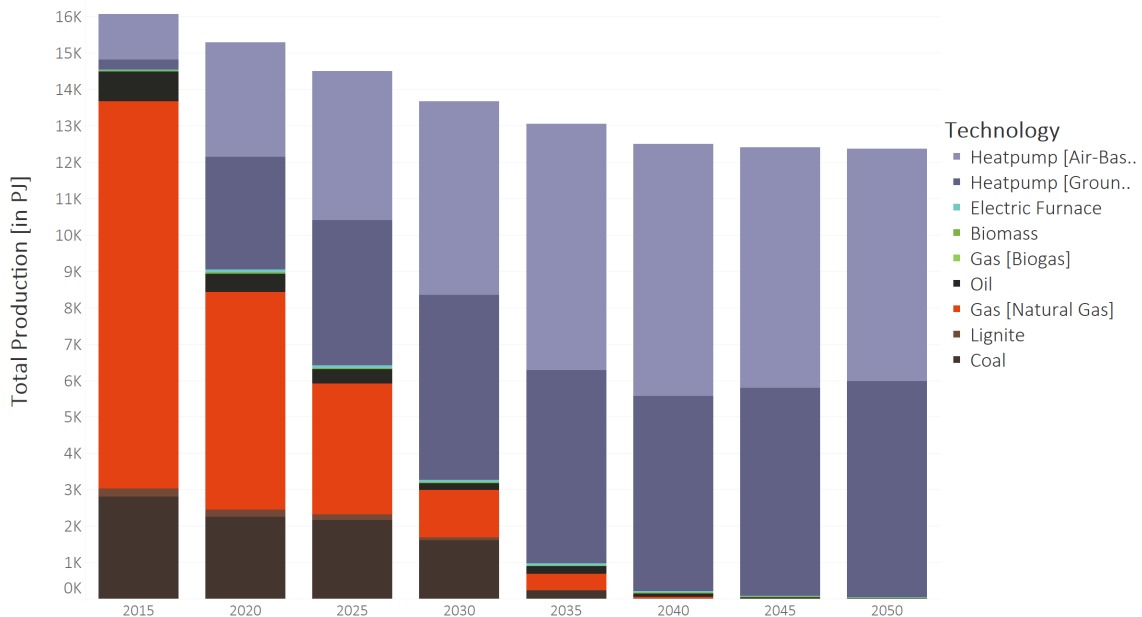


Figure 7: Yearly low-temperature heat production in the base scenario.

Source: Own illustration.

The high-temperature heating sector is the most difficult to decarbonize. Figure 8 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 (H₂) does not become a viable option in the 2° pathway. In the years from 2050 on, however, a shift towards H₂ could likely be observed. Also, with decreasing costs of power generation, electric furnaces could become an even more prominent technology.

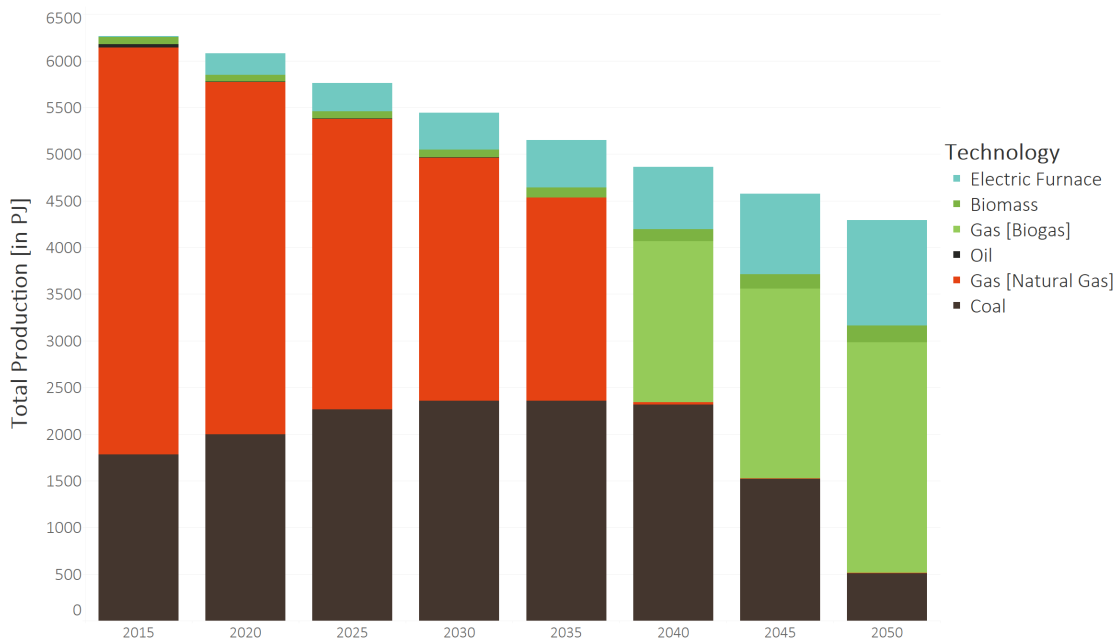


Figure 8: Yearly high-temperature heat production in the base scenario.

Source: Own illustration.

Figures 9 and 10 are showing 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, most existing Diesel-electric trains are phased out in the 2020s and replaced by fully electric trains. 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.

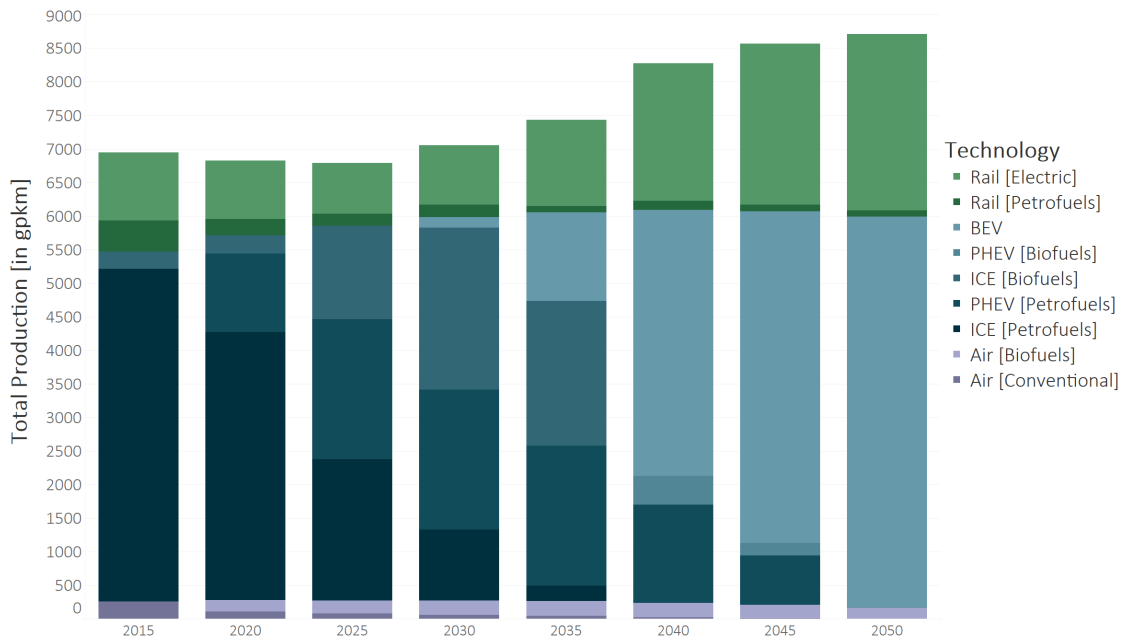


Figure 9: Development of passenger transportation services in the base scenario.

Source: Own illustration.

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

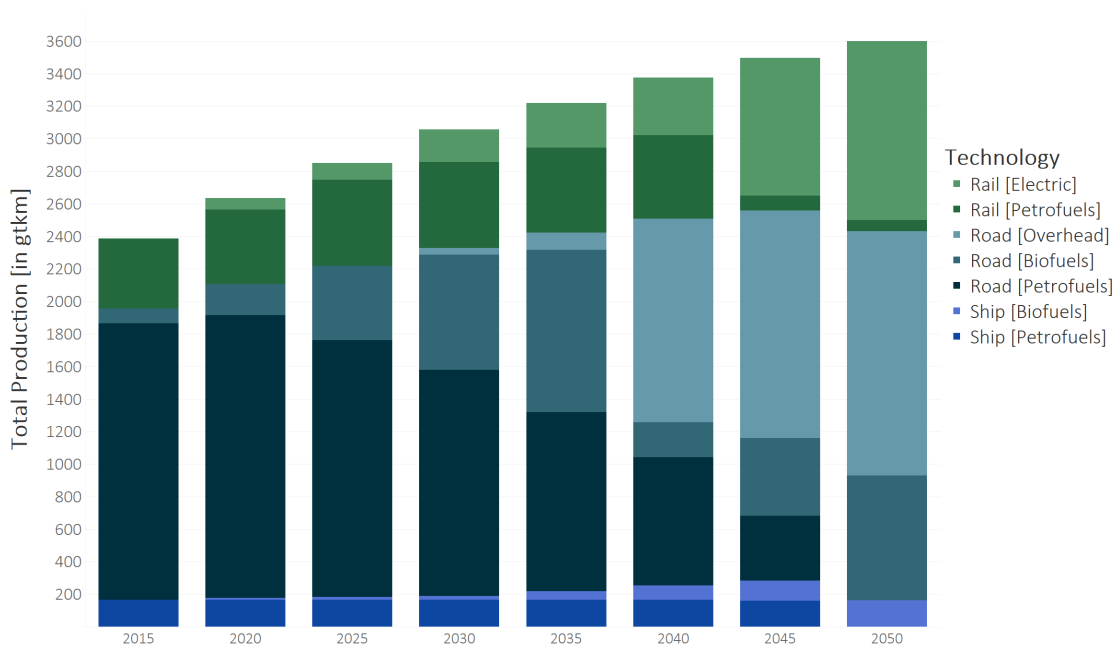


Figure 10: Development of freight transportation services in the base scenario.

Source: Own illustration.

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 other means of transportation. While the main reason for that lies in the set-up and nature of the model (i.e. a linear cost optimization constraint by capacity expansion limits), further analysis or limitations of this rapid phase-out will have to be conducted in future work. Concluding, similar to the passenger transportation sector, freight transportation is about 95% decarbonized by 2050, due to high shares of electric HGV and biofuels.

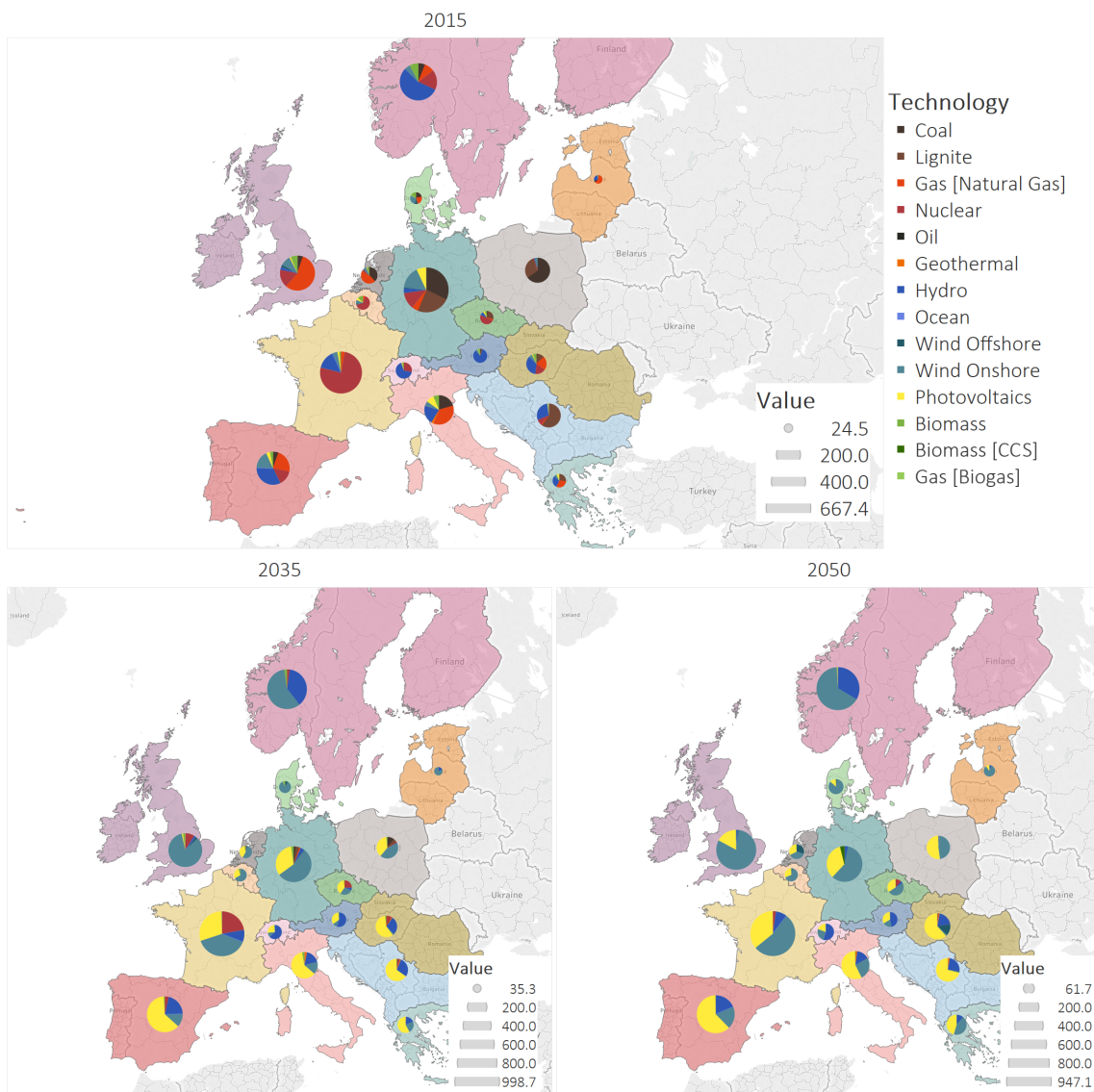


Figure 11: Regional power production in 2015, 2030, and 2050 in the base scenario.

Source: Own illustration.

On a regional level, it can be seen 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 2030. This trend is continued until 2050, where the alternative technology is constructed more, due to the limitations of potentials that have been reached previously.

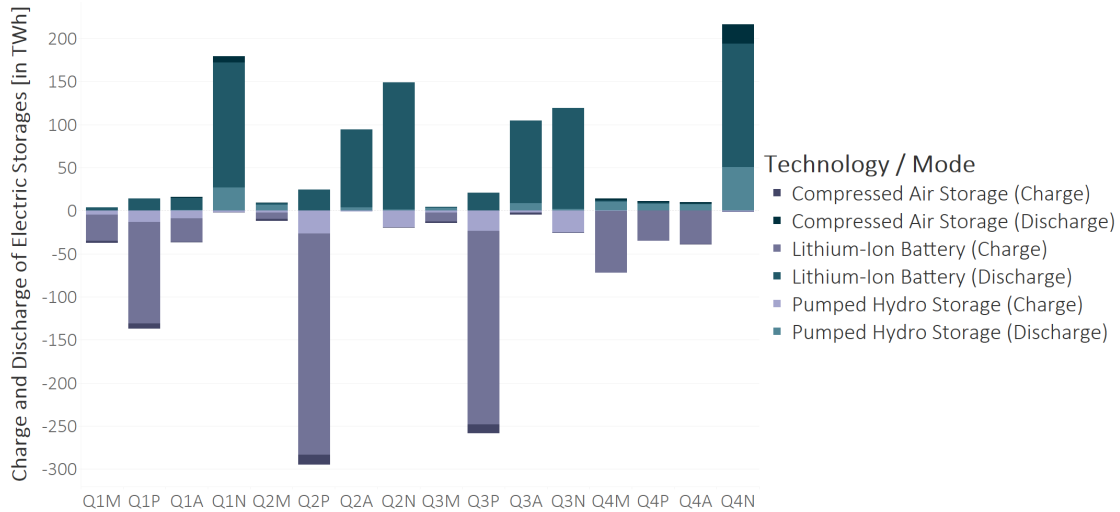


Figure 12: Charge and discharge of electric storages in 2050 in the base scenario (per time slice).

Source: Own illustration.

Observing the high shares of RES in 2050, their variability and flexibility have to be considered. Therefore, storages play an important role of balancing these loads. Figure 12 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 as seasonal energy storages. Their stored energy is mostly discharged in the winter months to compensate the inferior capacity factors of RES. The maximal peak-amount of charging or discharging storages in Europe is around 250 TWh and thus less than 5% of the yearly power production.

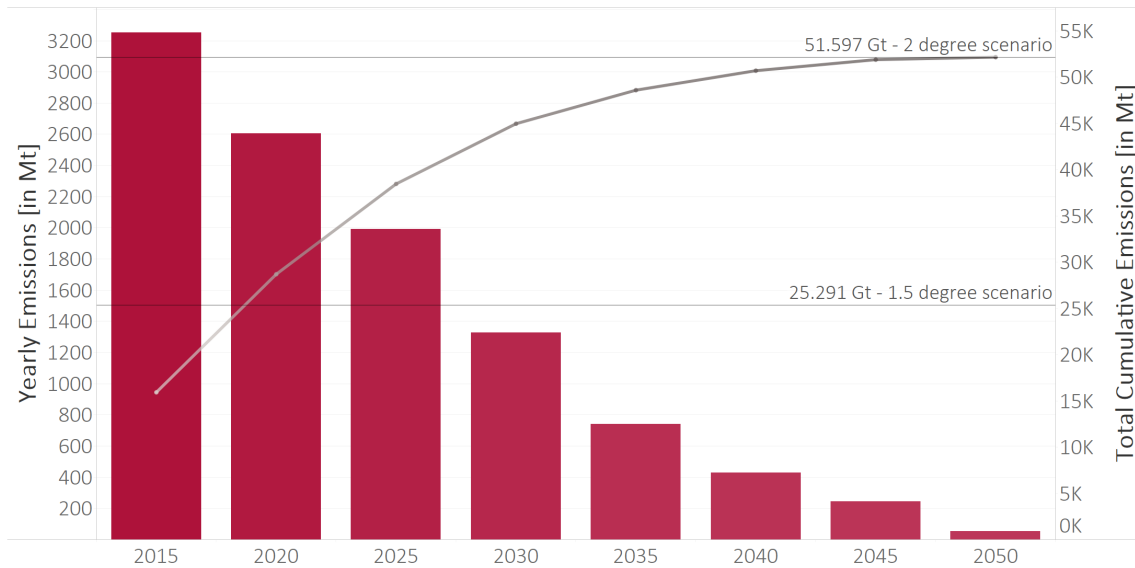


Figure 13: Cumulative CO₂ emissions in the 2° pathway.

Source: Own illustration.

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° goal. Figure 13 graphs the cumulative emissions over all regions per year. The red bars show the total emissions in this period, 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° budget by 2020.

4.2 Emission pathway: business as usual

In the business as usual (BAU) pathway, the model faces a carbon budget of 137.39 GtCO₂, almost triple the amount of the baseline 2° pathway. This means that model emissions meet a very relaxed constraint, enabling many regions to use more of their fossil fuels for a longer period. The total carbon budget is not reached in any of the distribution scenarios, as renewable energy sources still beat fossil-fueled power plants in terms of future cost efficiency. Even though the model would, in theory, be able to emit more CO₂ and thus construct new fossil power plants, it decides against it on a cost basis, resulting in a total carbon amount of 67.94 GtCO₂.

Figure 14 shows the development of electricity generation over the modeling period. The results are very close to the 2° pathway, indicating a substantial shift towards RES by 2045, where more than 95% of power production is decarbonized. The main difference is the usage of lignite, which is phased out later than hard coal, contrary to the base scenario.

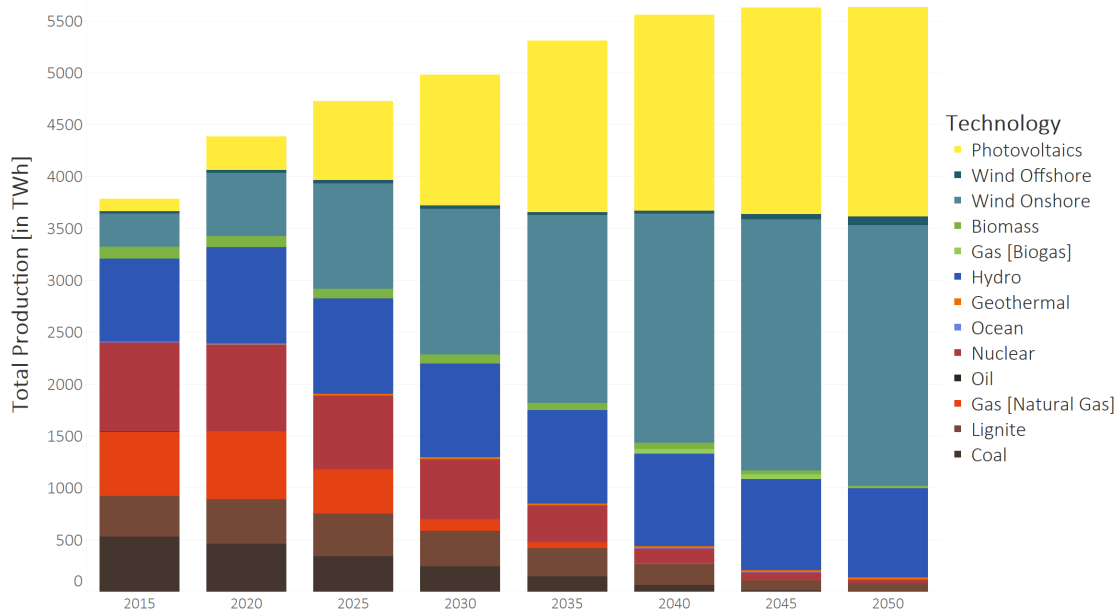


Figure 14: Development of yearly power production in the BAU pathway.

Source: Own illustration.

A much more prominent difference is the generation of high-temperature heat (figure 15), which, in the BAU scenario, is mainly based on coal as an energy carrier. While the gas capacities see the same fuel switch from natural gas to biogas as seen in the 2° pathway, coal is not phased out, and instead actually being used more up until the year 2040. Only then does the usage of hard coal as the preferred source for process heat decline, with biogas, and a small share of electric furnaces entering the mix.

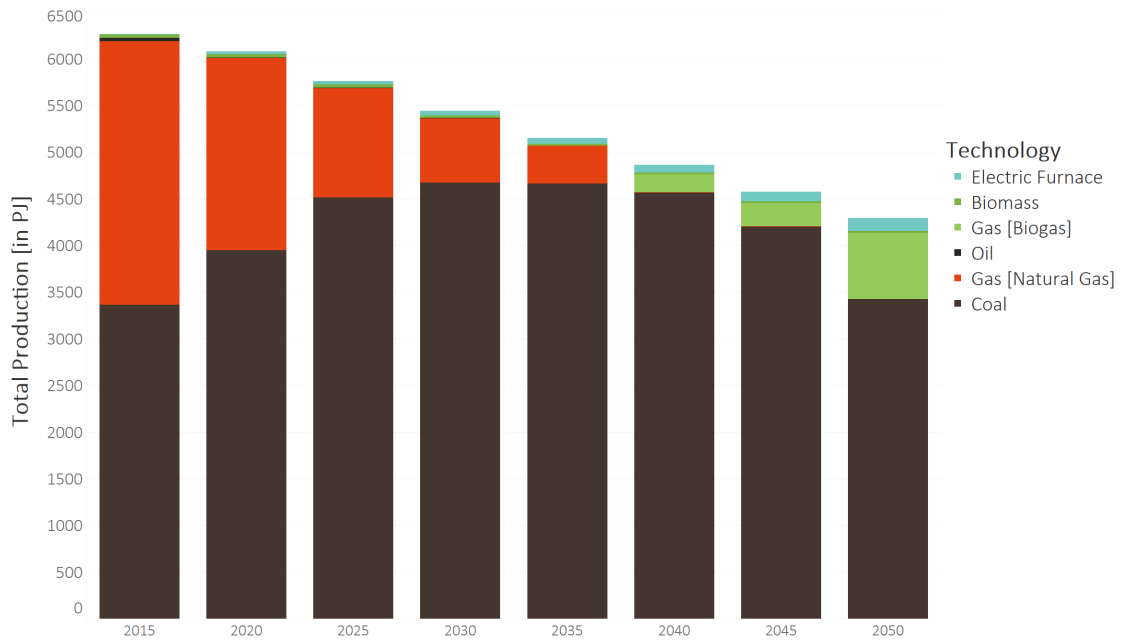


Figure 15: Development of yearly high-temperature heat production in the BAU pathway.

Source: Own illustration.

Another major difference between the emission pathways lies in the freight transportation sector. While overhead-powered trucks were the backbone of freight transportation services in the 2° pathway, the BAU scenario opts for bio-fueled combustion-based trucks instead.

The cumulative emissions in figure 16 show a total CO₂ output of 67.94 Gt, which is noticeably above the 2° pathway limit but does not reach the set maximum budget of just above 137 GtCO₂. This shows that for most sectors, renewables become increasingly competitive and are actually the lowest-cost solutions. The sector with the most difficulty of including RES is the high-temperature heating sector, where alternatives are costly.

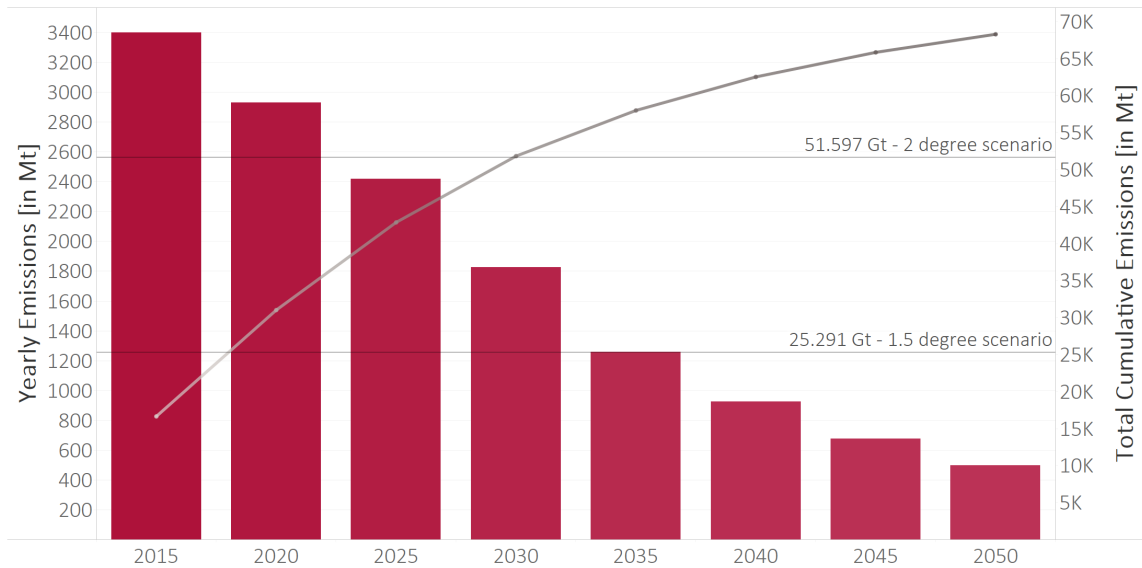


Figure 16: Cumulative CO₂ emissions in the BAU pathway.

Source: Own illustration.

4.3 Emission pathway: 1.5 degrees

As described in section 3, the 1.5° pathway has a total emission budget of 25.29 GtCO₂, which is not even half of the budget of the 2° pathway. Given today's emissions, this limit would be reached within the next four to five years. Thus, a drastic reduction in emissions – and possibly – negative emissions are needed.

Figure 17 shows the development of electricity generation over the years. The stricter carbon budget leads to a major change in the development of power generation. The sector is virtually decarbonized as early as 2030, with only nuclear power remaining in terms of conventional power sources. Bio-energy with carbon capture and storage (BECCS) is heavily used after 2020, as it is the only option for the model to achieve negative emissions and reduce the burden of current carbon emissions. Coal and lignite are phased out by 2025, with natural gas following in 2030.

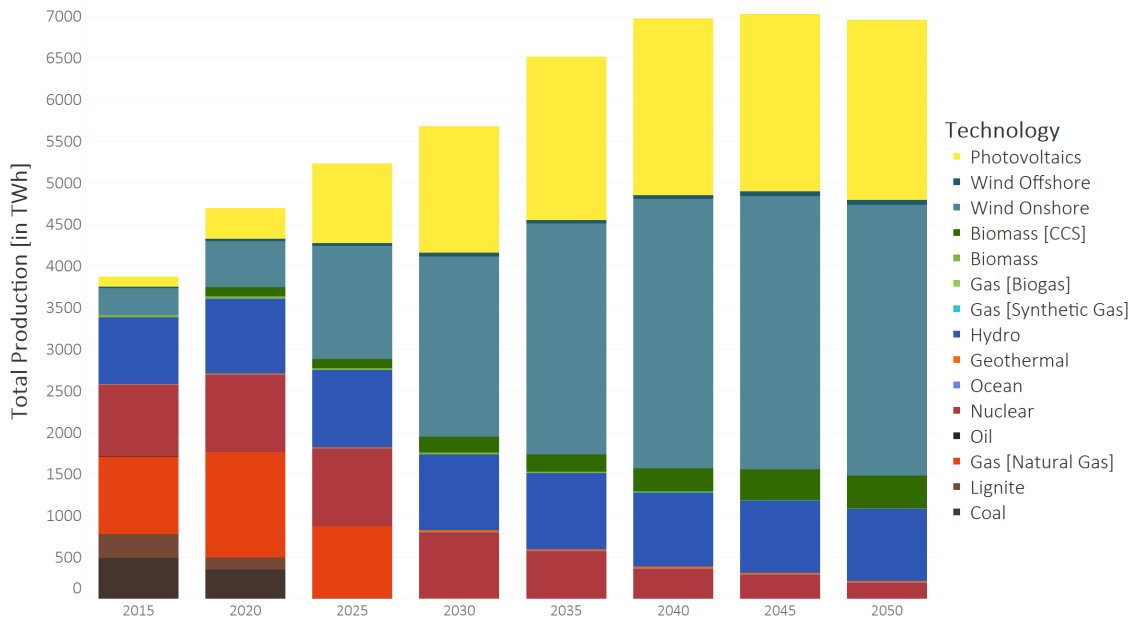


Figure 17: Development of yearly power production in the 1.5° pathway.

Source: Own illustration.

High-temperature heat also shows great diversion from both the 2°, as well as the BAU pathways. While coal is the dominant fuel source for high-temperature heat in both other pathways, the model opts for natural gas instead, in order to save on emissions. Electric furnaces play a much more critical role than in the other scenarios, as it is one of the few options for emission-free process heat generation. Biomass, which would be the other option, is instead used in CCS processes to generate negative emissions.

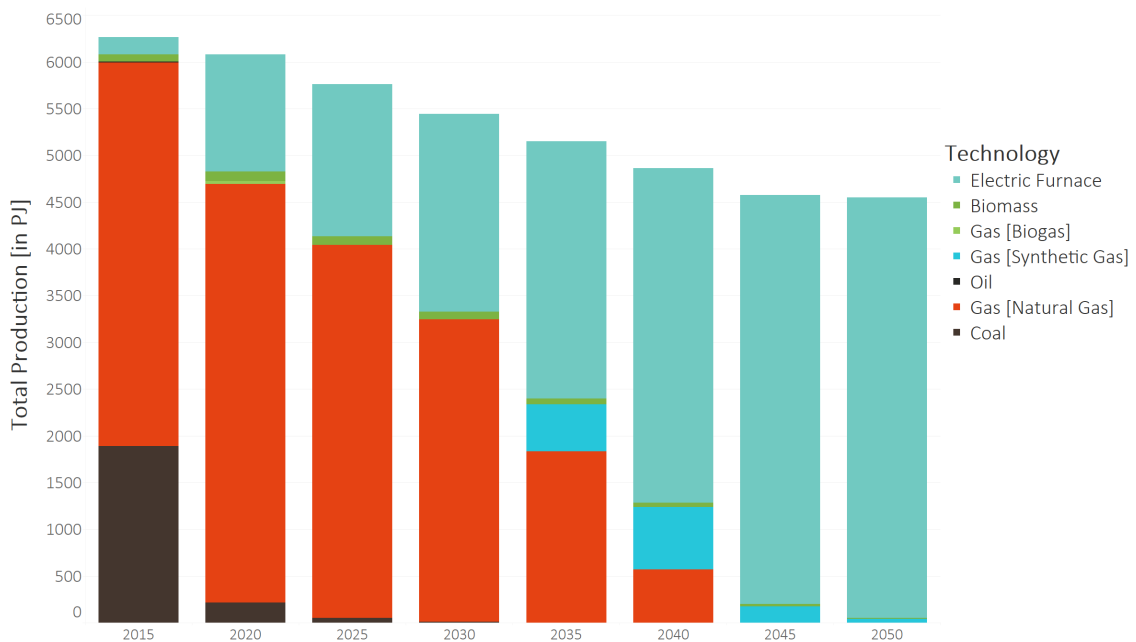


Figure 18: Yearly high-temperature heat production in the 1.5° pathway.

Source: Own illustration.

Freight transport in 2050 is based solely on overhead-powered trucks for road-based transportation, contrary to the other emission pathways. As soon as the technology becomes available at low costs, a fast switch towards electricity-based freight transport can be observed. While parts of the existing fleet of trucks remain in the system, all new capacities from 2035 onward are electric trucks, powered by overhead lines.

The cumulative emissions graph (see figure 19) shows an very different slope from the other pathways. For the first time, net negative emissions can be observed and occur from the year 2040 onward. Due to the limitations for the expansion of RES and the existing capacities being largely fossil fuel-based, the model reaches a peak amount of cumulative emissions of 28.14 GtCO₂ in 2030, before then reducing it again via the usage of BECCS. In the end, the budget of 25.60 GtCO₂ is met, complying with a 1.5° Celsius (C) pathway.

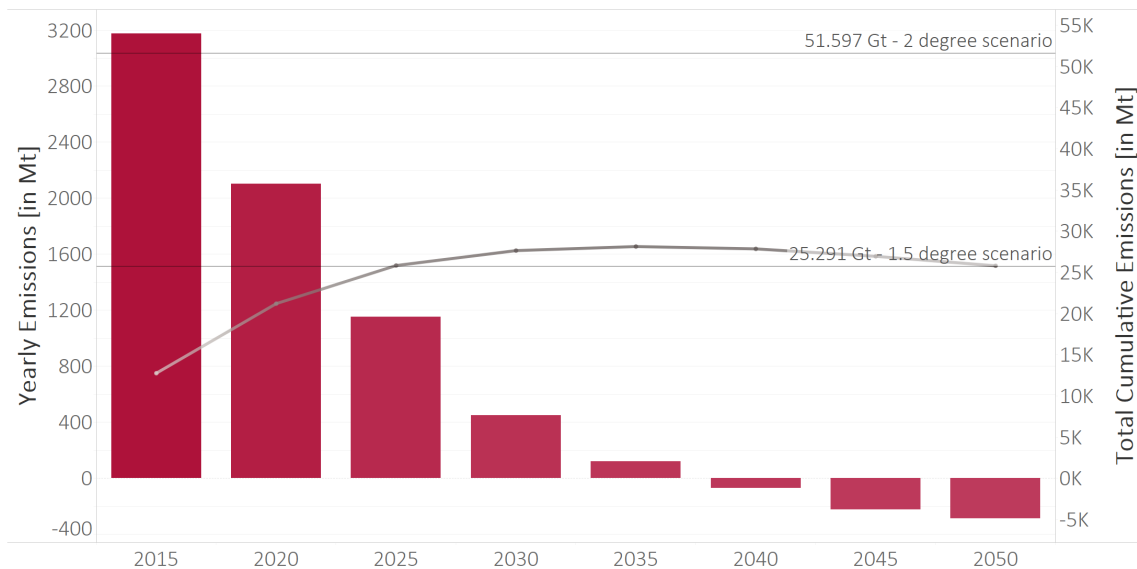


Figure 19: Cumulative CO₂ emissions in the 1.5° pathway.

Source: Own illustration.

4.4 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 most CO₂ distribution scenarios, although some distributions of the carbon budget do not yield a (technically) feasible solution. Figure 20 shows a comparison of total costs, relative to the base case (2° pathway, free distribution of emissions).

As expected, the 1.5° pathway nets the highest total costs, at least 15.7% higher than those of the 2° pathway. The BAU pathway is cheaper overall, albeit only by about 1.4% 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.

Scenario	Free Distribution	Share by Current Emissions	Share by GDP	Share by Population	Free Distribution (BECCS disabled)
1.5° pathway	15,7%	Infeasible	Infeasible	40,9%	Infeasible
2° pathway	0,0%	0,3%	Infeasible	1,0%	0,3%
BAU pathway	-1,4%	-1,4%	-0,9%	-1,4%	-1,4%

Figure 20: Cost comparison of all emission pathways and distribution scenarios. Relative change in total costs compared to the 2°, free distribution, scenario.

Source: Own illustration.

Whereas a change in distribution only nets a cost difference of about 1% in the 2° pathway, for the strict emission targets of the 1.5° pathway, the difference is tremendous. A difference of around 25% between the (technically) feasible distribution scenarios can be observed, with the "Share by GDP" and "Share by Current Emissions" scenarios being impossible to solve for the model, given the constraints - especially when it comes to grid stability concerns.⁹ It needs to be highlighted that the feasibility of achieving the 1.5° target is coupled to the availability of net-negative emission technologies (here 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 (Hirschhausen, Herold, and Oei 2012). However, given the very tight carbon budget and the current yearly emissions of Europe, an overshoot of the carbon budget for 1.5° seems almost unavoidable and can only be coped with via

⁹The usage of CCS can thus be explained by the model struggling to meet strict emission targets when considering the inertia of energy systems in the real world.

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.

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° 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%.

4.5 Discussion

4.5.1 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 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. 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.

4.5.2 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) and Jacobson et al. (2017b)). 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 2.2.4) 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%.

The results (depicted in figure 21) 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.

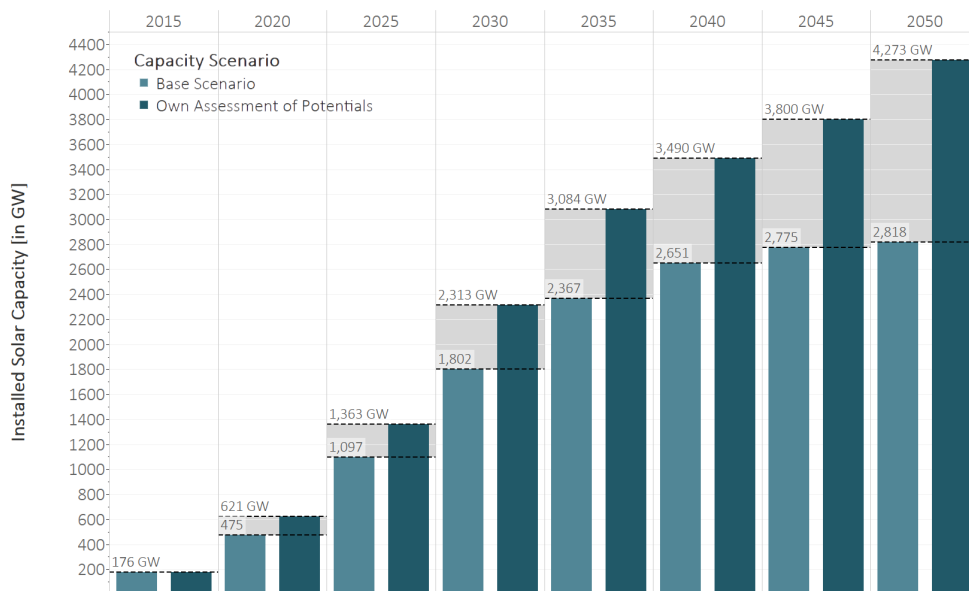


Figure 21: Development of installed solar capacities in both reference case and alternative assessment.

Source: Own illustration.

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.

4.5.3 Greenhouse gas emissions

When looking at GHG emissions, it has to be clearly differentiated between carbon dioxide (CO₂) and carbon dioxide equivalents (CO₂e). Whereas the former can be relatively easily used as a proxy to measure emission by taking outputs from power plants and industrial processes into account, the latter is more complex to analyze. Nevertheless, CO₂e has the ability to express other GHG emissions, such as Methane (CH₄) or Nitrous oxide (N₂O), in terms of CO₂, based on their relative global warming potential (GWP). The GWP describes a relative measuring unit of the impact of a GHG on the global warming. To calculate the CO₂e potential of GHGs, their respective GWP is multiplied by their amount.¹⁰

Currently, our model only takes CO₂ emissions into account, but especially when looking at natural gas and its role in the low-carbon transition, other GHGs have to be considered. Because of its high energy content and the low CO₂ emission in comparison to coal, natural gas is often considered a backup solution for RES or as bridging fuel towards a largely decarbonized scenario (Cremonese and Gusev 2016). Despite its advantages over coal and oil, significant quantities of methane, which is an even stronger GHG than CO₂, can be emitted into the atmosphere from natural gas production (Howarth 2015). Thus, the implemented GHG in our model will be extended in the future and a budget of CO₂e and not only CO₂ will be given. This is likely to lead to even less natural gas in the energy mix. Additionally, the emissions budgets taken from the IPCC (2014) are based on carbon dioxide equivalents. Thus, no conversion from CO₂ to CO₂e has to be done and more reliable results of regarding the climate change can be made.

Furthermore, the available European CO₂ budget underlies the same problems regarding a fair share of the national budgets as stated in section 3. Especially the distribution of the global budget by taking emissions into account has to be critically questioned. European countries faced a relatively homogeneous industrialization and thus the difference between the "historical responsibility" and the

¹⁰e.g., 1t of CH₄ with a GWG₁₀₀ of 25 equals therefore 25t of CO₂

"responsibility for the future" concept by the WBGU (2009) is neglectable. Nevertheless, this differentiation has to be made for model runs with fixed emission shares on a global scale. The emission share for Europe, by population, approximates the emissions that were allocated by Europe in the global runs of GENeSYS-MOD v1.0 (Löffler et al. 2017b), but further analyses have to be done in the future.

5 Conclusion

Over the last decades, a trend of climate warming has arisen and sparked a heated debate about the emission of greenhouse gases. If the concentration of these GHGs is not reduced significantly within the near future, irreversible and severe consequences for humans and natural systems are the consequence (McMichael, Woodruff, and Hales 2006). One of the biggest contributors of GHG emissions is the energy sector, accounting for more than two thirds of the global emissions (IEA 2016). The most important greenhouse gas is CO₂, which is responsible for more than 80% of the emissions in the energy sector (Foster and Bedrosyan 2014). 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, a linear program, minimizing total system costs for the sectors power, heat, and transport, given external constraints, such as emission limits. 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,¹¹ 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° C, a 1.5° 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

¹¹Instead of the previous six time slices.

for the set carbon budget have been examined: free distribution,¹² share by GDP, share by population, and share by current emissions.¹³ The results indicate that even ambitious climate targets can be met, both technically and economically. Most modeled pathways and distribution scenarios were solvable, except for some distributions in the 1.5° pathway, which did not yield any feasible solution. It can be shown that reaching a climate target of 2° C only nets a cost increase of about 1.5%, while reducing total emissions by more than 30% compared to the BAU case. 1.5° are achievable too, but the 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.

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.

The power sector sees a steady phase-out of fossil fuels across all pathways, usually starting out slowly from 2015 to 2020, with 2025 to 2030 usually representing large sums of fossil capacities going off-grid. This is due to old capacities growing obsolete, as well as renewables becoming more and more competitive. While overall electricity demands decline, the total power generation jumps from about 3,600 TWh to about 5,100 TWh in 2050, as a strong coupling between the usually segregated sectors can be observed. Storages play an important role of balancing grid infrastructure and demands, with about 739 gigawatt (GW) of installed storage capacities in 2050, most of which are Lithium-Ion (Li-Ion) batteries. The high-temperature industrial heat sector is the most difficult to decarbonize, which is shown over the course of the different pathways. Renewable alternatives for process heat are expensive and difficult to implement, which means that fossil fuels play a significant role for high-temperature heat generation, given the emission budget.

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

¹²Meaning endogenous optimization on a cost-minimizing basis, calculated by the model.

¹³Considering 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 short term.

temporal setting of the model, there are still limitations to the amount of variability that can be observed with the setting. Especially for quickly fluctuating renewables, the model could profit from an even finer temporal resolution, but it would come with serious other negative implications for the model.

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 the fast phase-out of fossil generation capacities. 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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