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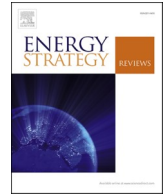
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Modeling the low-carbon transition of the European energy system - A quantitative assessment of the stranded assets problem

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ABSTRACT

In this paper, multiple pathways for the European energy system until 2050 are computed, focusing on one of the major challenges of the low-carbon transition: the issue of unused capacities and stranded assets. Three different scenarios are analyzed, utilizing the Global Energy System Model (GENeSYS-MOD) for calculations. A major feature is the introduction of limited foresight and imperfect planning to the multi-sectoral approach of the model. A swift transition towards renewable energy sources is needed in order to ensure the goal of staying below 2 °C is maintained. This leads to the underutilization of current fossil-fueled plant capacities, an effect compounded by the prioritization of short-term goals over long-term targets. In the worst case, capacities with a combined value of up to 200 billion € corresponding to 260 GW total capacity may end up stranded by 2035, with significant shares in the coal and gas sectors. Contrary, in the baseline scenario featuring perfect foresight, this amount can be reduced by as much as 75%. Thus, the need for strong, clear signals from policy makers arises in order to combat the threat of short-sighted planning and investment losses.

1. Introduction and literature review

As a leading economic force, Europe has to play a key role in the transition towards renewable energies. This is supported by the broad amount of research on the topic, especially the electricity sector [1–4]. Coal, as well as other fossil-fuel phase-outs are being enforced across multiple European countries, while ambitious climate goals are being set among members of the European Union [5,6]. But the lobbying of incumbent actors, as well as a general political inertia, might lead to challenges concerning the fulfillment of set climate goals. As many European countries *already* face overcapacities of energy generation facilities (across multiple sectors), stranded asset problems might arise, potentially disrupting a swift transition towards renewables [7–10].

In general, multiple definitions used in various contexts of stranded assets exist in different fields of study [11]. Through this paper, we use the definition of stranded assets proposed by Caldecott, Howarth, and McSharry [12]: “stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities”.¹ This definition is widely accepted in existing literature regarding stranded assets [11].

In the last decade, the debate about stranded assets in the energy system gained drastically in importance and consideration. Several recent studies and reports outline this growing relevance. A report from the Carbon Tracker Initiative [14] compared the production of coal, natural gas, and oil for all sectors of the International Energy Agency (IEA) 450 ppm with a business as usual scenario. It concluded that no new coal mines are needed, and furthermore that projects with a value of 2 trillion US\$ of capital expenditures are in danger to end as stranded assets. A recent study by Mercure et al. [15] comes to a similar result. They assess future energy demand projections and changes in fossil fuel assets value. Their results show that a substantial fraction of the global fossil fuel industry may end stranded, presenting a total wealth loss of 1–4 trillion US\$. In addition, high volumes of valuable resource are being spent unnecessarily. In general, a trend can be identified, where, driven by climate goals, high shares (50–80%) of fossil fuels could become stranded, a phenomenon also known as “carbon bubble” [16].

Previous studies have shown that massive expansions of renewable generation capacities are needed in order to stay within the agreed upon goal of a 2 °C, or aiming at 1.5 °C, mean temperature increase, and that nuclear power is not an economically feasible alternative [17,18]. The

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¹ For another definition of stranded assets see, for example, the Carbon Tracker Initiative [13].

issue becomes even more important when considering the SR1.5 of the IPCC [19]. Still, new conventional-fueled power plants are constructed across Europe, albeit declining load factors [20]. Therefore, a continuation of current trends has the potential to cause lock-in effects and a severe stranding of assets and resources. Clear signals to prevent such a market failure are missing until now from a policy side [21].

Hence, the future investments into the fossil fuel sector, most notably coal, have to be reduced. This is especially important, as Pfeiffer et al. [22] found that the global capital stock for the power sector consistent with a 50% probability of global warming of 2 °C was reached in 2017. They, and others, conclude that new electricity generation assets must be low-carbon or they may end stranded otherwise [10,22]. Johnson et al. [7] conclude similar findings. They emphasize that the construction of coal power plants, especially without installed CCS technology, would have to be reduced significantly, emphasizing the use of existing capacities over new construction. Also, they argue that both natural gas and coal-based power generation without CCS have to be phased out to limit the mean global warming to 2 °C and, even more for 1.5 °C. A similar finding regarding natural gas is presented in an article by Conor et al. [23] for a distinct regional application. Their study looks into different low carbon scenarios and assesses the utilization of Ireland's gas distribution network. They conclude that electrification of residential heating can lead to both a reduction of the utilization of the gas network, as well as the risk of large parts of the network being stranded or decommissioned. Furthermore, several cross-sectoral studies conclude overall similar findings [24–27]. For example, IRENA [24] shows high amounts of stranded assets in the buildings sector, mainly due to the slow and inert pace at which changes happen in this sector.

Still, further ignorance of the long-term risks of stranded assets by policy-makers and investors will further increase the aforementioned financial risk. This is also observable in developing countries. Bos and Gupta [28] look at the risks of investing in fossil fuel infrastructure for China and Kenya. The study finds that investing in renewable energy sources is highly favorable and needed to prevent assets from being stranded. Also, as presented by Green and Newman [29], the current development and deployment of renewable energy sources have features of disruptive innovation. Such innovation is fast-growing, expands to be a significant disruption to an established system, and inherently leads to stranded assets.

Neglecting long-term risks is often modeled in energy system models using myopic or limited foresight. Notable examples are the studies of Gerbaulet et al. [30] and Keppo and Strubegger [31]. Both articles limit the foresight of optimization models and feature similar results: A limited foresight leads to limited investments in renewable resources in the earlier modeling periods. This then leads to higher investments and stranded assets in later periods. Another approach was conducted by Fuso Nerini et al. [32]. With the help of a modified TIMES model, they analyze the impact of myopic decision making in the energy system of the United Kingdom. They show that myopic planning combined with slow technology diffusion rates could lead to a non-achievement of the climate targets of the United Kingdom. The current aging of the European power plant infrastructure poses chances to transition towards a low-carbon energy system when building renewable energy sources instead of fossil fuel generation capacities [2].

Energy system models are widely being used to assess the development and transformation of future energy systems [33]. Jacobsen et al. [4] and Bogdanov et al. [34] show with their analyses that the global power production can be based on solely renewable energy sources in 2050. Overall, the discussion about the feasibility of 100% renewable energy system (compare [35,36]) is not the scope of this article. Nevertheless, the studies mentioned above as well as articles by Pursiheimo, Hottinen, and Koljonen [37] and Deng, Blok, and van der Leun [38] conclude that the future energy system should be based on sustainable energy sources. In general, scenarios and models that are assessing future energy systems with large shares of renewables prove to fulfill more sustainable criteria [39–41]. In this context, Child et al. [39]

point out, that when considering the constraints of fossil CCS, it should not be accounted for as a sustainable technology option. Also, Oei and Mendelevitch [42] conclude in their assessment of CO₂ infrastructure investment that large-scale deployment of CCS is rather unlikely in Europe.

In general, many studies assess the development of the European power system [1,30,43,44]. Even the possibility of a 100% renewable electricity system for Europe is assessed in a study presented by Connolly, Lund, and Mathiesen [45]. They show that 100% renewable power generation is a distinct possibility. Similar findings that no fossil fuels are needed for a flexible energy system were also presented by Child et al. [46] recently. Hence, capacity additions of fossil power generation capacities are not needed for the future energy system of Europe.

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

The remainder of the paper is structured as follows: Section 2 pictures the current situation of the European energy system with respect to stranded assets. Section 3 briefly explains the model and introduces the scenarios, followed by a discussion of the results in Section 4 and a conclusion in Section 5.

2. Status quo

2.1. The current status of the energy system

The ongoing transition of the energy system has led to substantial additions of capacities. Driven by climate targets, fossil fuel cost changes, efficiency gains in renewable energy generation, and a different role of conventional energy, power plants were built despite capacities already being present [8,47]. In turn, higher shares of renewable energies led to a decreasing utilization of gas-fired power generation, even worsening with the trend of installing new capacities. This can be observed in various European countries, like Germany, Italy, the Netherlands, or the UK, where, between 2010 and 2015, the installed capacities of natural gas power plants increased by 10%, while the annual load factor of the same utilities dropped from more than 50% to around 30% (see Fig. 1). Similar, and in some cases even much stronger, effects are visible in other parts of the world, especially in India and China.

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

2.2. Current political landscape

The member states of the European Union (EU) have committed their agreement to the Renewable Energy Directive 2009/28/EC [49]. Thus, they are obliged to provide their National Renewable Energy Action Plan as well as defining renewable energy targets for 2020. Additionally,

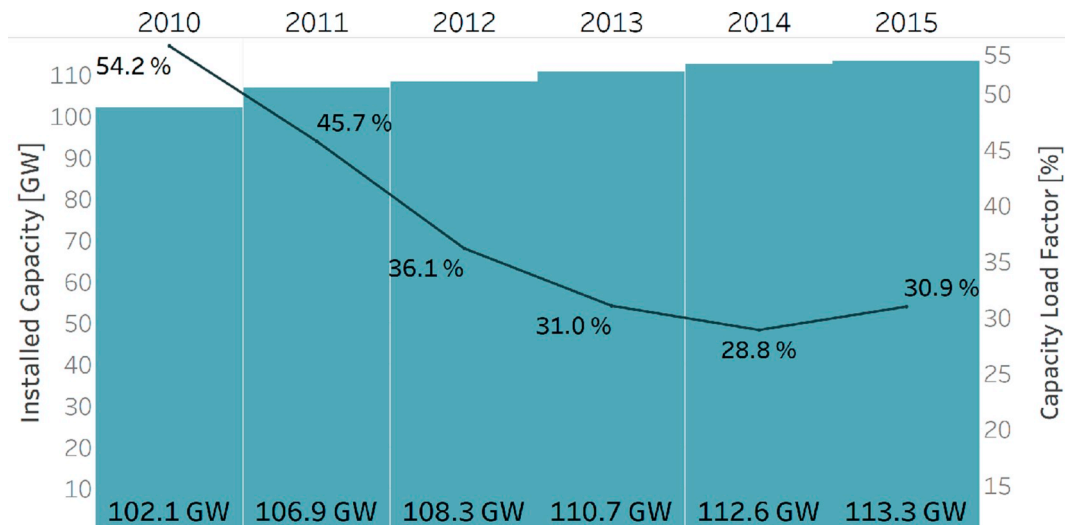


Fig. 1. Installed natural gas capacities and their yearly load factor for Germany, Italy, UK, and the Netherlands. Source: Own illustration, based on [20,48].

a further binding target for GHG emission reduction is adopted for 2030 [50]. Together with the EU's Nationally Determined Contribution (NDC) to the Paris Climate Agreement [51], each European member state sets explicit targets for their future energy systems greenhouse gas (GHG) reductions.

Still, the political discussion in the EU is twofold: First, some countries are promoting more ambitious climate targets. Most notably, France, Belgium, Denmark, Luxembourg, Netherlands, Portugal, Spain, and Sweden push for enhanced NDCs, and more ambitious climate politics as well as adopting a target for net-zero emission by 2050 [52]. Additionally, one of the prominent steps in the direction of creating an *Energy Union* in the EU is the recent decision of the countries Portugal, France, and Spain to develop strategic interconnections [53]. Also, in line with the current efforts of the European Commission, they propose to work on accelerating the energy transition by considering cross-border auctions on renewable energy production. Contrary, Hungary, Poland, Slovakia, and the Czech Republic (the so-called *Visegrád Four* countries) agreed on a common stance on the European Union's 2050 climate goals. In the recent negotiations of the European Council on a landmark climate strategy for 2050, the *Visegrád Four*, together with Estonia, protested at the inclusion of the explicit target year 2050 for reaching net-zero emissions [54].

However, a large share of the countries is currently not on track to meet these targets and thus, substantial acceleration from historical levels is required [55–58]. This especially includes countries with substantial shares of fossil power generation and high GHG emissions (e.g., Germany or Poland) [20,59], keeping the global mean temperature increase below 2 °C or even 1.5 °C will be harder to achieve.

Additionally, companies in Germany and Poland are still investing in the refurbishment and construction of coal power plants [47]. Other countries that are phasing out coal as primary power generation technology are investing into the construction of additional natural gas power plants [60,61]. Although these are less carbon-intensive, they will likely end up being stranded as well, if the EU-wide targets for 2050 are enforced [62,63].

As an example, Germany was one of the leading countries for transforming their energy system within the frame of the so called *Energiewende* [64]. This rapid addition of renewable energy sources (RES) was mainly made possible by to the German Renewable Energy Sources Act (EEG) [65] which lead to a significant increase of RES in the electricity sector from 7% in 2000 to nearly 36% in 2017 [66]. Albeit this significant change in the power sector, limited success of decarbonizing the other sectors, i.e. heating or transportation, and current policy changes regarding RES expansion make it likely that Germany

will fail to reach. The 2020 EU target [56,67].

A further issue might be the strong influence of the energy industry on the policy- and decision-makers [68,69]. Together with other interest groups, like labor unions and other affected energy intensive industry branches (e.g. the steel industry), the lobby for conventional energy sources has a prominent effect on the current politics and, therefore, on the pace of transforming the energy system [70]. Another significant barrier which might lead to a failure of the 2020 GHG targets are considerations of national (energy) security and other idiosyncrasies [71]. Hence, populist governments are less likely to promote RES than left-wing ones [70]).

3. Model and data

The model utilized in this study is the Global Energy System Model (GENESYSMOD), an open-source linear optimization model, encompassing the sectors electricity, heat, and transport of the energy system.² For information on the general model formulation and the European dataset, see Refs. [72,73]. A stylized graphical representation of the model can be seen in Fig. 2. Europe is divided into 17 nodes, each representing a country or geographic region. Demands for electricity, passenger & freight transport, as well as for low- and high-temperature heat are given exogenously via scenario assumptions (see Ref. [73]), with the model seeking to meet the required energy demands in each time slice. To achieve this, the model calculates the optimal capacity investments into generation and storages, the usage of sector-coupling technologies, and thus the resulting energy mix.

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

Scenario 1. BASE: Follows the baseline scenario of [62], staying below a 2° Celsius climate target with a resulting CO₂ budget of 51.97 GtCO₂ for Europe for the years 2015–2050. Emissions are distributed endogenously, and the cost-optimal pathway is calculated based on a social planner's perspective with perfect foresight.

Scenario 2. RED: Introduces reduced foresight to the model. The calculations only encompass a limited time horizon of 5 years (which might correspond to the limited perspective of election periods of 4–5 years or some business concepts). The model optimizes the energy system for 2015, 2020, and 2025 with reduced foresight, taking the resulting production values and constructed capacities of the previous

² GENESYS-MOD is based on the Open Source Energy Modeling System (OSeMOSYS) and further expands its features.

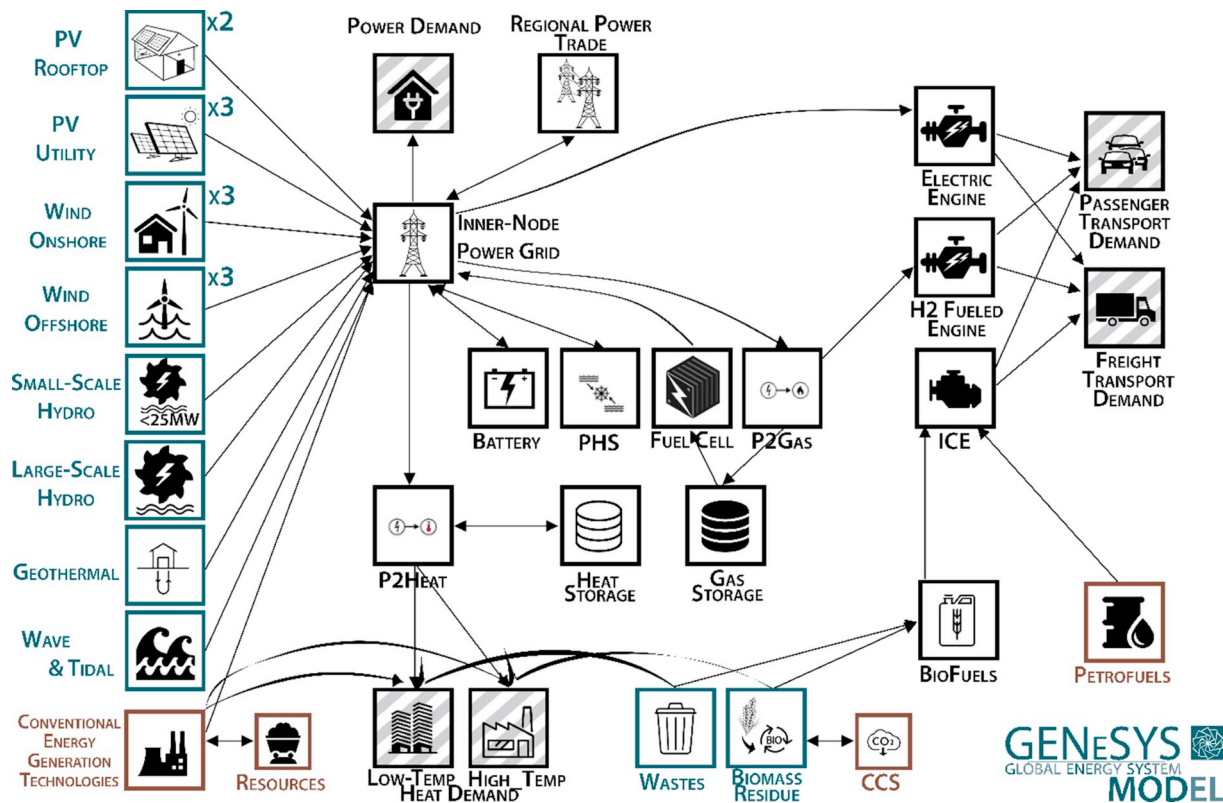


Fig. 2. Model structure of GENeSYS-MOD v2.0. The model differentiates between two different kinds of rooftop PV (residential, commercial), and three categories of utility PV, onshore, and offshore wind (optimal, average, and inferior for utility PV and onshore wind; shallow, transitional, and deep for offshore wind). Source: Own illustration.

optimization step as given. After 2025, the model optimizes the pathway towards 2050, trying to uphold the 2 °C limitations.

Scenario 3. POL: Adds additional political constraints to the reduced foresight scenario. Since real-life policy decisions are not always cost-optimal, and instead driven by lobbying groups, incumbent actors, and interested parties, the current political landscape, as described in section 2.2, is taken into account. It is assumed that regional targets for renewable energies (see Ref. [5]) are not overachieved, thus representing an upper barrier for the model. Also, existing conventional generation lifetimes are extended as a policy measure. Again, starting at 2025, the model realizes the importance of the 2 °C target and starts the regular optimization process (cost-minimizing; upholding climate constraints) from 2030 onward.

Common for all scenarios is a carbon budget of 51.97 GtCO₂. This budget is calculated by using the global carbon budget found in the *Fifth Assessment Report* of the Intergovernmental Panel on Climate Change [74]. Updated calculations with a changed methodology have resulted in different higher CO₂-budgets within the 1.5SR. The chosen budget of 51.97 Gt CO₂ is therefore equivalent to a 2 °C target (with respect to the older estimations) or a below 2 °C target (with respect to the newest estimations). Exogenous emissions (such as cement production or LULUCF) that are not included in GENeSYS-MOD are further excluded from this budget. The remaining amount is then distributed to the modeled region by using the population as an indicator. A graphical representation of the process can be found in Appendix B. For further information, refer to Burandt et al. [73].

The computational process of the reduced foresight analyses is depicted in Fig. 3. The model computes the optimal capacity investments and energy mixes at that specific point in time and uses these results as given decisions of the past when conducting the next optimization step.

4. Results

The model results show that reduced foresight does affect the short-term decision making process when it comes to long-term goals such as climate targets. This effect is further increased if political drivers delay, or even prevent, the theoretically cost-optimal measures. Adherent to that, the RED scenario shows a total cost increase of about 5% in total system costs. The POL scenario is the most expensive, with an increase of 6.2%. This is due to additional assets being built, but quickly becoming obsolete when a strict CO₂ target is implemented. The costs of the implemented lifetime extensions of the POL scenario are however, not included in the scenario run and therefore would even worsen the comparison. All three scenarios manage to uphold the below 2 °C goal, and are thus *technically* feasible, but the shorter planning horizon leads to shifts in energy use and a swifter need for emission reduction in the later years, which, in turn, leads to an increase in unused capacities and stranded assets. Fig. 4 shows the changes in the relative primary energy mix for the years 2020, 2030, 2040, and 2050. The scenarios running under reduced foresight both see an increased utilization of natural gas, as well as lignite until 2040. Compared to the BASE scenario, natural gas serves as more of a bridging technology (mainly in the heating sector), whilst the BASE case sees a swifter transition towards RES, especially onshore wind energy. Nuclear is more prominent in the POL scenario, where politically driven lifetime extensions keep nuclear in the mix. Due to the heavily increased emissions in the earlier periods, bio-energy with carbon capture, and storage plays a role in the POL scenario as negative emission technologies are needed in order to facilitate the achievement of climate goals.

Figs. 5 and 6 show the unused generation capacities resulting from the model calculations. A clear distinction between the three scenarios can be made, with POL consistently showing the highest amounts of unused generation capacities. From a geographical standpoint, regions

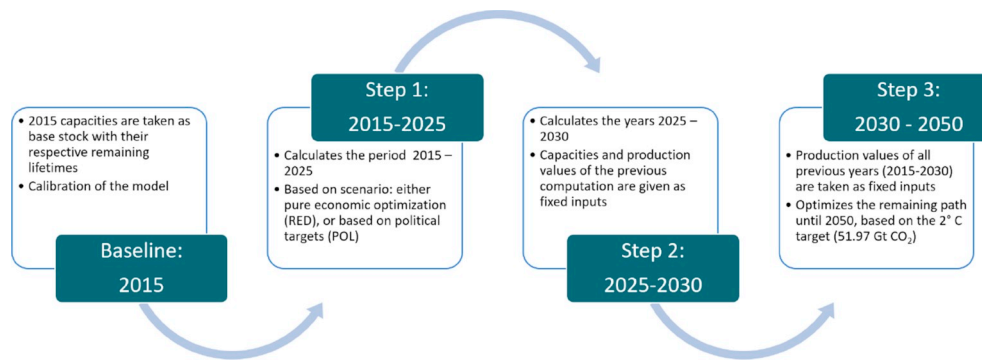


Fig. 3. Computational process of the reduced foresight scenarios (RED & POL). Source: Own illustration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

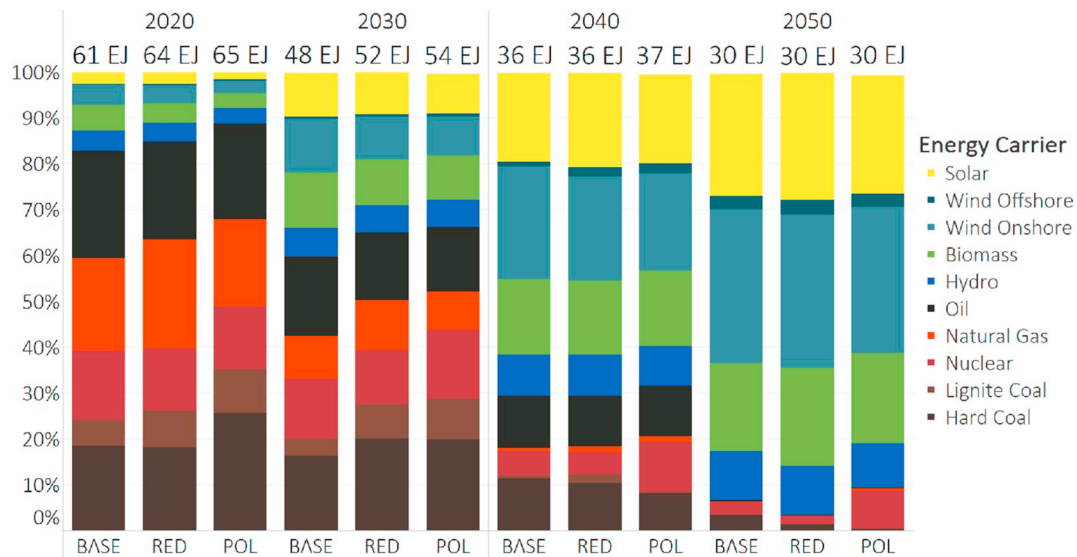


Fig. 4. Primary energy supply for the years 2020, 2030, 2040, and 2050, both relative, as well as total amount in Exajoule (EJ). Source: Own illustration.

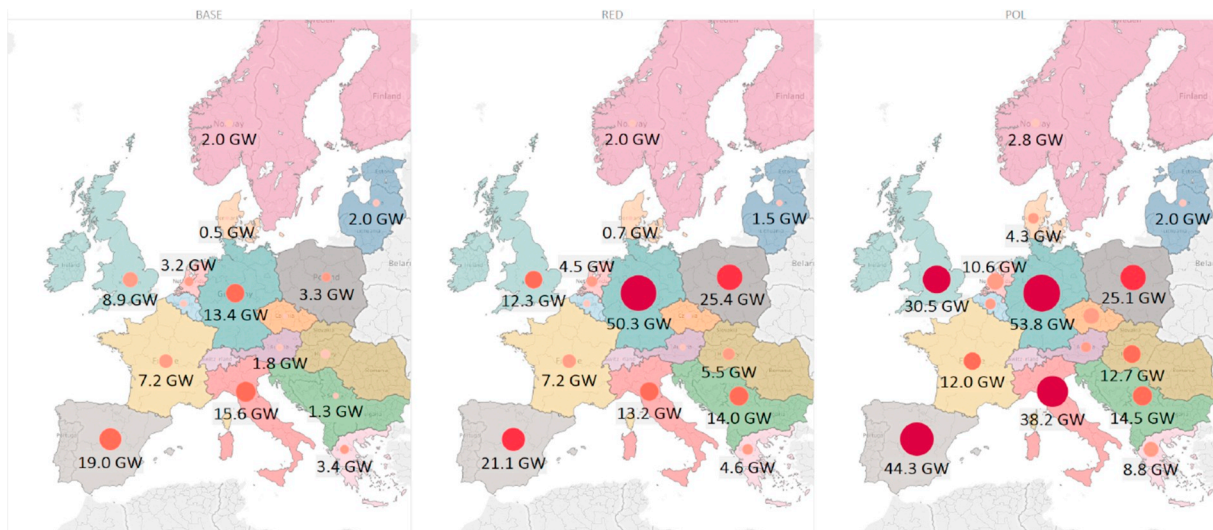


Fig. 5. Total stranded assets for coal- and gas-fueled power generation per region in the year 2035. Source: Own illustration.

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

Under reduced foresight, especially cheap and local power from

lignite is preferred in the short-term, leading to (stranded) over-capacities in the later years (when climate targets become binding). The lifetime extensions of the POL scenario further increase this effect,

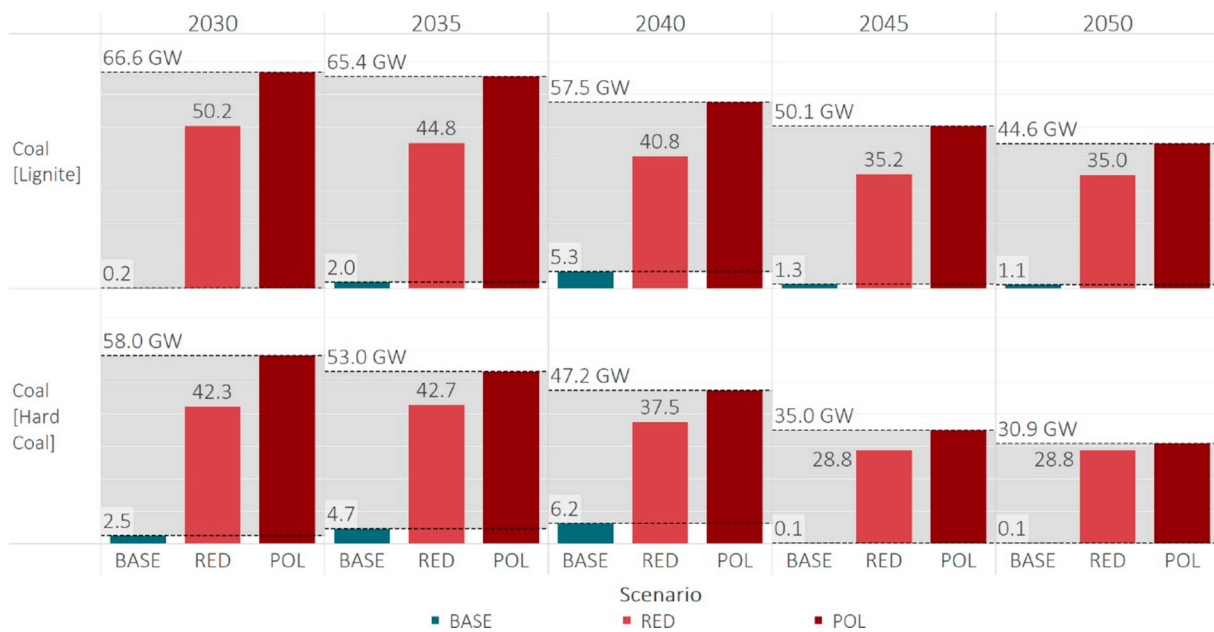


Fig. 6. Total amount of unused capacities for coal-based power plants. Source: Own illustration.

leading to vast amounts of underutilized plants. As depicted in Fig. 6, around 120 GW of hard coal and lignite coal are unused in 2035 in the POL scenario as compared to 6.7 GW in the BASE scenario. Using the capital costs of 1600 € per kW for hard coal and 1900 € per kW for lignite coal respectively, 105 billion € of capital are stranded by 2035. This amount significantly increases to 200 billion € when taking the 145 GW of unused gas-fired capacity into account. The RED scenario sees a similar high amount of stranded capacity of coal and gas with 87 GW coal and 110 GW gas-fired in 2035, corresponding to around 150 billion €. Only in the BASE scenario with perfect foresight, the amount of unused capacity (with the inherent risk of stranded capital) is significantly reduced. In 2035, the BASE scenario sees 76 GW of unused gas capacities in addition to the aforementioned 6.7 GW in coal assets. This equals an amount of 50 billion € 67% less than in the RED and 75% less than in the POL scenario, respectively. This showcases the importance of long-term planning and decision making when climate goals are to be enforced.

Fig. 7 shows the development of total gas-fired generation capacities, as well as their load factor for all three scenarios until 2040. In the

medium term (2020–2039), gas-based power plants are most commonly used in the BASE scenario, where they serve as a relatively low-emission alternative to coal- and lignite-based generation. They are also partially used in conjunction with bio-gas, reducing their emission intensity even further. POL sees the highest installed capacities, but also the lowest utilization factors for the gas plants. Comparatively expensive gas is replaced by cheap coal, reducing the load factors. After 2035, with the sudden ‘realization’ of urgent need for climate action (see the scenario descriptions in section 3), fossil gas cannot be utilized due to extremely tight carbon constraints, causing load factors to decline even further.

Having to meet a CO₂-budget in line with the 2 °C climate target, a shift in emissions between the different sectors and time periods can be observed for the three scenarios. Fig. 8 shows the difference in emissions per sector, compared to the BASE scenario. Especially in the earlier years of the modeling horizon (where the reduction of foresight takes place), emissions are vastly higher in the electricity sector. The overall system cost is increased due to having to match these shortfalls in the earlier periods with additional decarbonization measures in the heat and

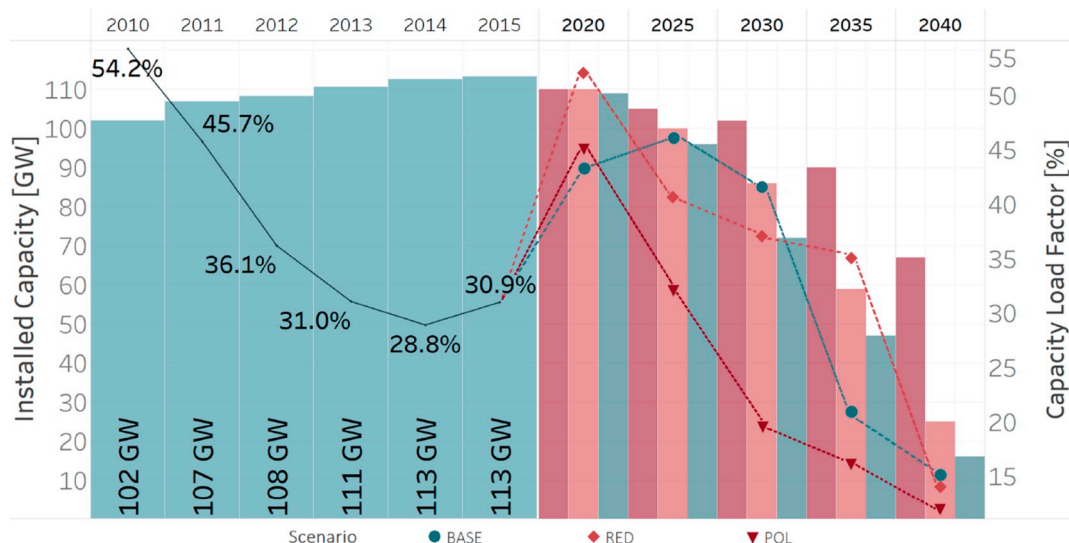


Fig. 7. Gas power plant capacities and load factor for Germany, Italy, UK, and the Netherlands. Source: Own illustration, data for 2010–2015 based on [20,48].

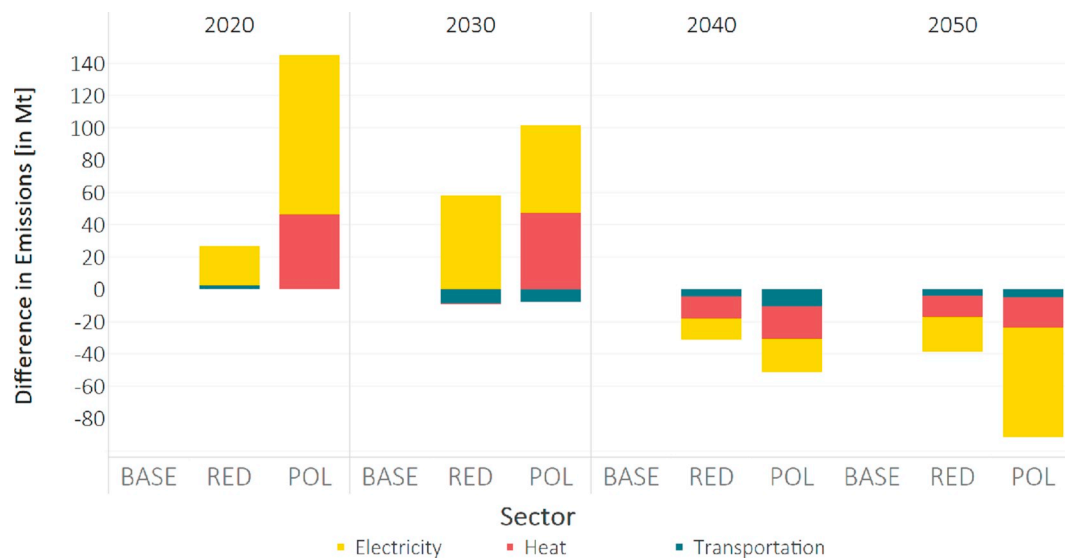


Fig. 8. Emission differences between scenarios for the sectors electricity, heat, and transportation in Mt CO₂ in comparison to the Base scenario. Source: Own illustration.

transport sectors, mostly in the form of bio-fueled options and a shift from coal to gas in the heating sector. In the later years, most of the shift in emissions lies in the heating and power sectors. The only way to achieve the carbon budget for the POL scenario is by using costly negative emission technologies, which additionally comes with severe other social and environmental issues [75,76].³

Social cost analysis. While potential stranded capacities and investments of businesses are an important concern about moving forward with the low-carbon transition, policy makers should also factor in social costs and benefits in their decision making process. The burning of fossil fuels causes significant damage to health and environment. A recent study of the German *Umweltbundesamt* (the German Environment Agency) shows that an internalization of such negative externalities would raise the necessary carbon price to about 180€/tCO₂ [77].

Fig. 9 shows a sensitivity analysis of levelized costs for key technologies with regard to different CO₂ prices by comparing the social cost value of 180€/tCO₂ to the current EU Emissions Trading System (ETS) price (29€/tCO₂ in August 2019 [78]). It can be clearly demonstrated that given a carbon price that reflects the actual damages, renewable technologies provide the cheapest source of electricity. This holds true even for already operational fossil-fueled plants (e.g. the capital cost part being zero). With the predicted decline in capital costs for renewable technologies in the upcoming years (see Appendix D), this effect is even increased, with some RES already being the cheapest form of electricity even at relatively low CO₂ prices.

This means that constructing new renewable power plants would actually be cheaper (from a social benefit standpoint) than using the existing fossil-fueled power plants. This finding further underlines the previous results, highlighting that when long-term climate goals (which align with social welfare improvements) are prioritized over short-term decision-making, no additional investment in new or existing fossil power plants should be done. Also, implementing policies that maximize social benefits (by minimizing social costs), such as implementing a CO₂ price that reflects the actual negative externalities, would achieve the necessary effects and drive fossil generators out of the market (as long as fossil subsidies do not distort these market characteristics).

³ Also, methane leakage is not included in the scope of the model when considering CCS technologies.

5. Conclusion

The European energy system is on the brink of change. To achieve the ambitious climate goals, a transition of the energy system away from fossil fuels and towards renewable energy sources is needed. However, there is an ongoing debate about the actual implementation of possible pathways and the challenges involved. Substantial capacity additions over the last few years, coupled with changes in capital and fuel costs, energy efficiency gains, and a different role of conventional energy, have led to overcapacities already being present in the energy system [7–9]. While an omniscient, cost-optimizing planner is often used in optimization models, real-life decisions are usually based on incumbent parties, political influence, and imperfect foresight [68]. This paper introduces two new scenarios, *RED* and *POL*, featuring reduced foresight for the years up until 2030. The *POL* scenario also includes political boundaries, representing the imperfect decision-making process of policy makers that often have to compromise. These boundaries include the assumption that national targets for renewable integration will not see an over-achievement, and lifetime extensions for conventional capacities (due to incumbent actors exerting their power, fear for job losses, and energy security concerns). The results show that there could be massive amounts of unutilized -and thus stranded - capacities in Europe in the upcoming years if climate targets are taken seriously. The *BASE* scenario, which includes perfect foresight out of a social planner's perspective, already sees substantial amounts of stranded capacities in the medium term if a climate target of below 2 °C is to be met (roughly 85 GW in stranded capacities, corresponding to about 50 billion € in investment losses). Introducing reduced foresight similar to short-sighted political and business strategies to the model further increases this problem, as it leads to an over-construction of conventional generation capacities in the 2020s that quickly become obsolete and underutilized (*RED* scenario: 150 billion €, *POL* scenario: 200 billion €). The decreasing competitiveness of conventional energy generation poses difficult challenges for investors, owners, and policy makers, as issues such as stranded assets and job security arise. Also, forcing premature shutdowns of generation facilities often leads to legal disputes about damages due to profit losses by the generators (such as currently being seen in Germany with nuclear power providers and the coal commission findings [79,80]). However, additional results from a social cost analysis show that environmental and health damages, when considered, heavily influence the cost-competitiveness for fossil-fueled power plants. This further increases the need for strong and clear

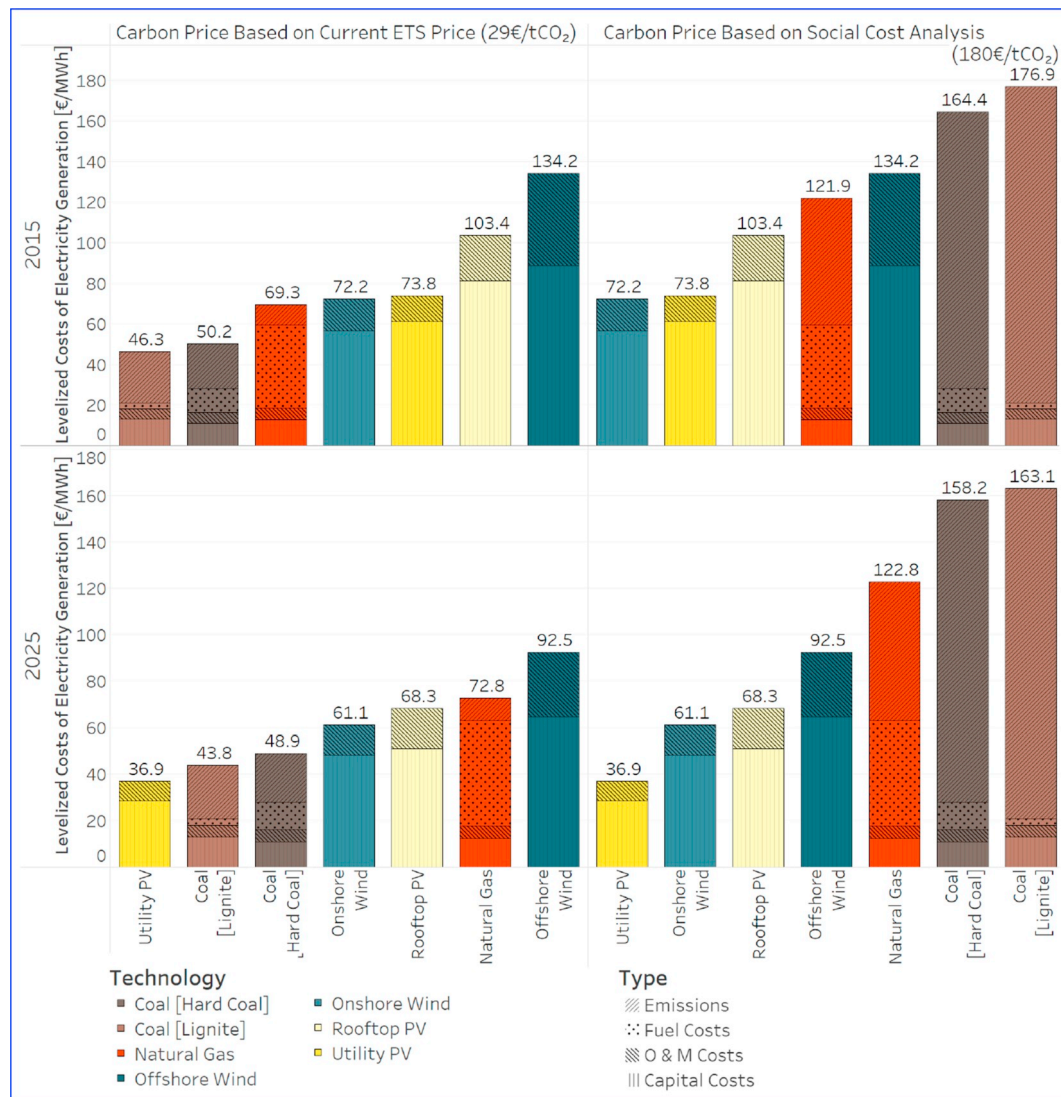


Fig. 9. Levelized cost analysis for key technologies (Average across the modeled regions). Levelized costs are computed given for two different CO₂ prices: left shows the merit order for a CO₂ price based on current European Emissions Trading System (ETS) prices [78], whereas the right-hand side shows a CO₂ price based on an internalization of negative external effects [77].

signals from policy makers, which are needed to prevent construction of unnecessary fossil-fueled power plants and combat the threat of investment losses and wasted resources that could increase significantly when short-term goals are prioritized over long-term targets. Further research is required for the issue of stranded assets in other sectors or regions, which are not covered by our work.

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Appendix A. Model description

GENESYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission targets, integration of renewables, and sector-coupling. The model minimizes the objective function, which comprises total system costs (encompassing all costs occurring over the modeled time period) [72,81].

The GENESYS-MOD framework consists of multiple blocks of functionality, that ultimately originate from the OSeMOSYS framework. Fig. 10 shows the underlying block structure of GENESYS-MOD v2.0, with the additions made in this study (namely the option to compute scenarios with reduced foresight, as well as some additional data for the policy-driven scenario).

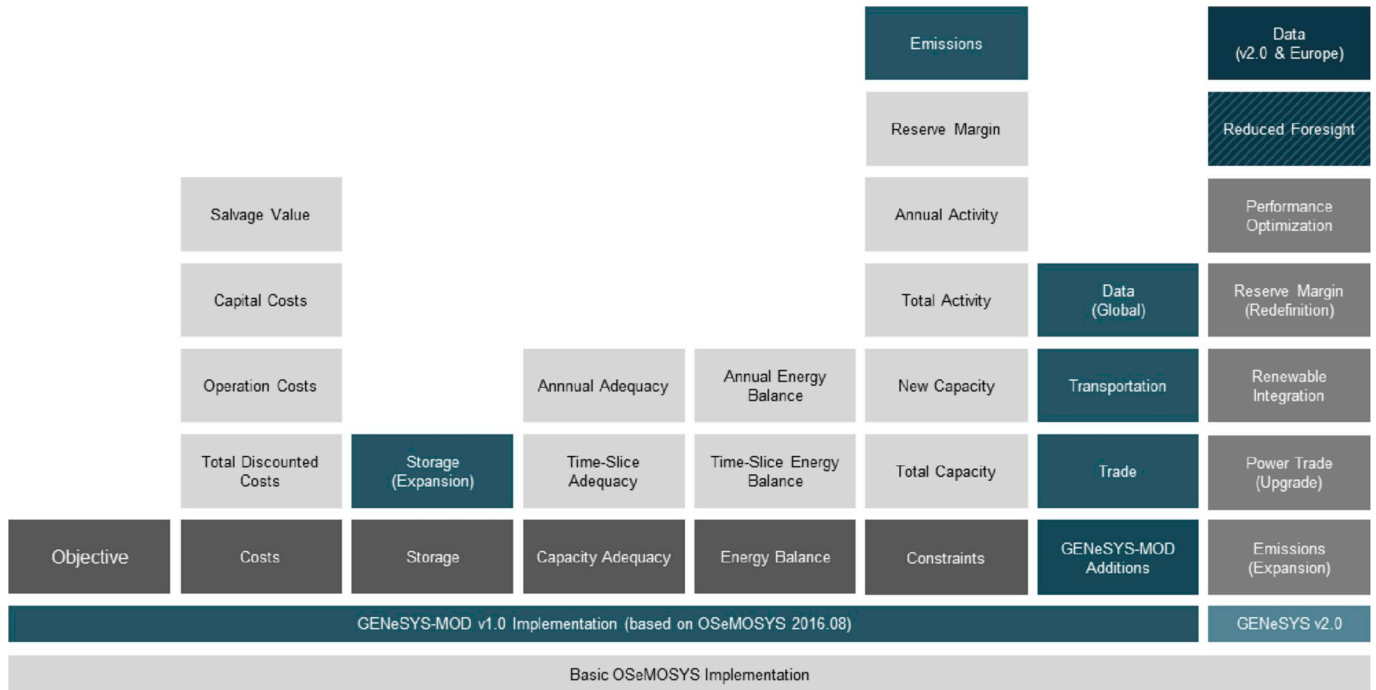


Fig. 10. Model structure of the GENeSYS-MOD implementation used in this study.

(Final) Energy demands and weather time series are given exogenously for each modeled time slice, with the model computing the optimal flows of energy, and resulting needs for capacity additions and storages.⁴ Additional demands through sector-coupling are derived endogenously. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g. to limit the useable potential of renewables), RES feed-in (e.g. to ensure grid stability), emission budgets (given either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and yield realistic results. The GENeSYS-MOD v2.0 model version used in this paper features a total of 16 time slices per year (each quarter of a year with a specific type-day, consisting of four time slices each). The years 2020–2050 are modeled in 5-year-steps. All input data is consistent with this time resolution. Since GENeSYS-MOD does not feature any stochastic features, all modeled time steps are known to the model at all times. There is no uncertainty about e.g. RES feed-in. The model allows for investment into all technologies⁵ and acts purely economical when computing the resulting pathways (while staying true to the given constraints). It usually assumes the role of a social planner with perfect foresight, optimizing the total welfare through cost minimization. In this paper, an add-on allowing for myopic foresight using multiple computational stages, is introduced. All fiscal units are handled in 2015 terms (with amounts in other years being discounted towards the base year). For more information on the mathematical side of the model, as well as all changes between model versions, please consult [72,73,81].

⁴ GENeSYS-MOD offers various storage options: Lithium-ion and redox-flow batteries, pumped hydro storages, compressed air electricity storages, gas (hydrogen and methane) storages, and heat storages.

⁵ Except when given fixed, predetermined phase-out dates, such as for nuclear in Germany, or coal in Great-Britain. For more information, please consult [73].

Appendix B. Emission budget

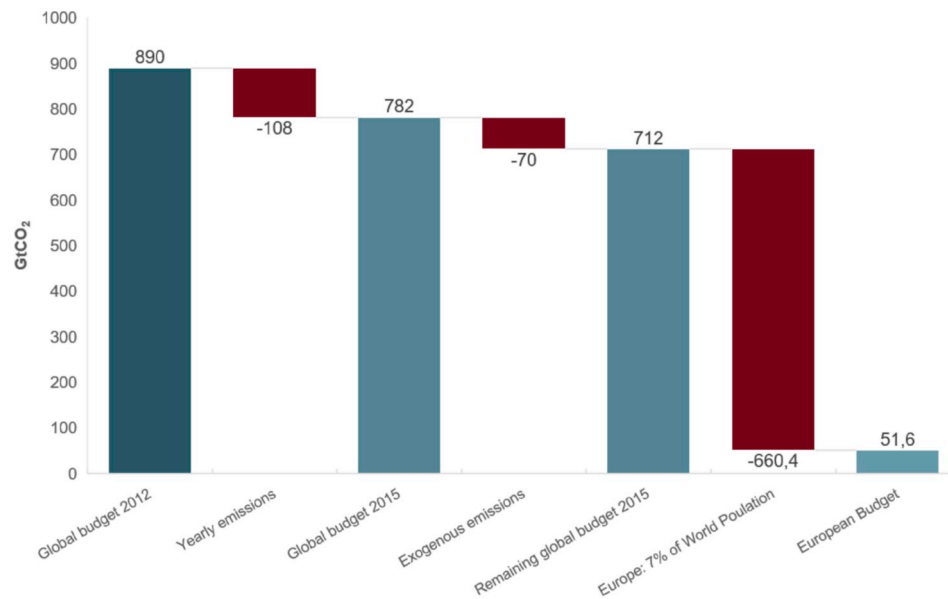


Fig. 11. Emission budget calculations.

Appendix C. Validation of model results

To validate the model results, the computed values for the base year 2015 have been compared with real-life statistical data to ensure proper functionality of the energy system model. Fig. 12 shows a comparison of model results with historic data for power generation (upper left), emissions per sector (upper right), and primary energy supply (bottom).

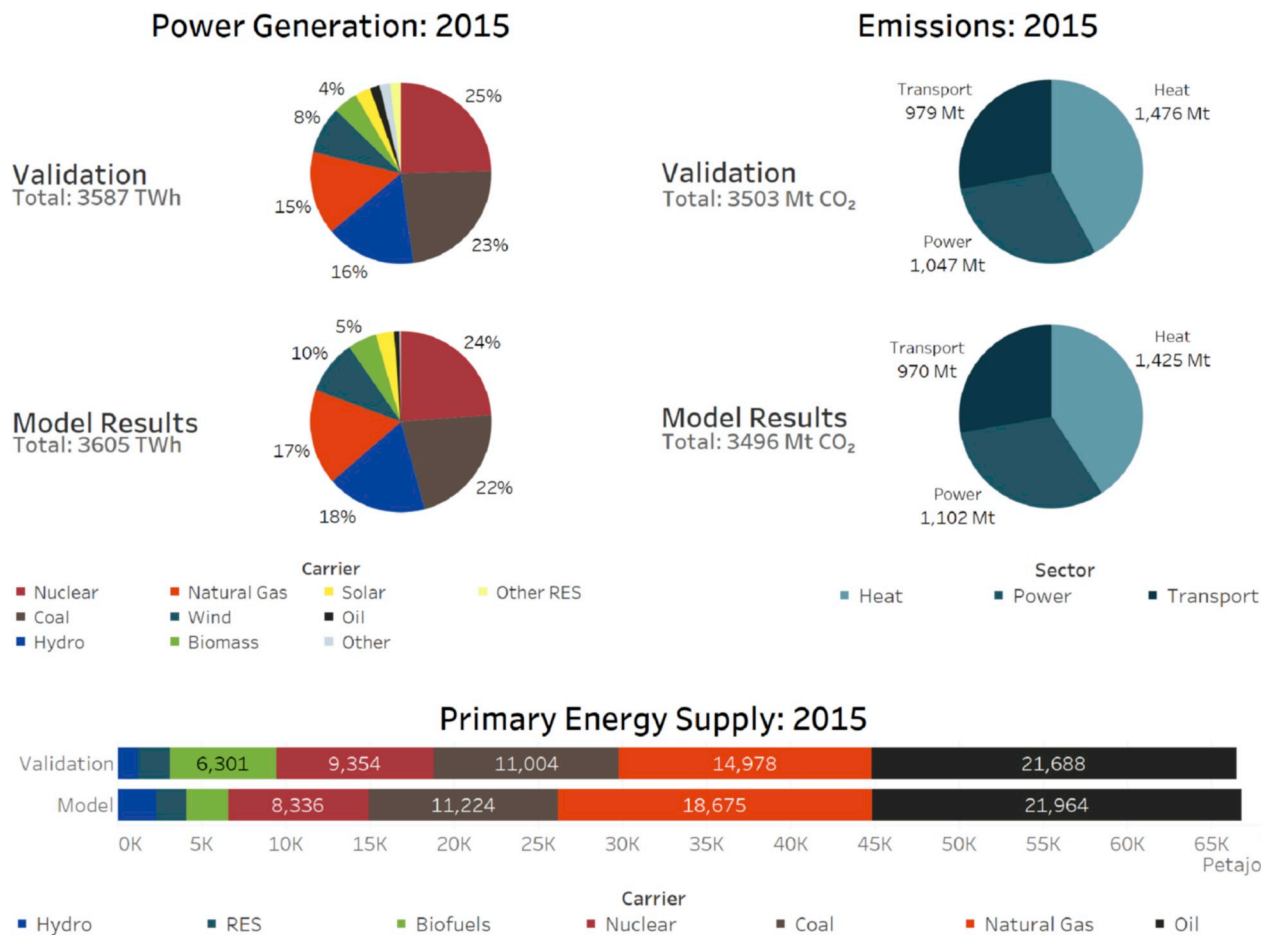


Fig. 12. Comparison of 2015 model results vs. historical numbers.

Source: Own calculations, 2015 data based on [82–87].

Results show that the model numbers are reasonably close to real-life values, usually only diverting less than 1% from historic values (0.5% for total power generated, 0.2% for total emissions, 0.8% for primary energy supply). While there are a few differences between energy carriers and technologies, this usually stems from existing overcapacities in Europe, where the model is able to perform some “optimization” towards later periods, given the perfect foresight character. We can see that in the power sector, renewables are a bit over-represented (hydro with 18% vs. 16%, wind with 10% vs. 8%, etc.) and fossils a bit under-represented (nuclear with 24% vs. 25%, coal with 22% vs. 23%, etc.), except natural gas, which makes up for 17% of the power sector instead of real-life 15%. Albeit their existence, all these differences are small enough to be considered very close to real-life numbers. The largest difference in numbers lies in the primary energy supply, where natural gas makes up a significantly higher share in the model, while biomass/biofuels see less utilization. This difference mainly comes from the heating sector, where biomass sees less utilization than in historic 2015. A possible explanation for that is the fact that we, in the model, only include second and third generation biofuels, meaning that non-sustainable biomass products are disregarded, driving up the costs for the biomass value-chain. In the end, though, these differences end up in a very similar total primary energy supply.

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

Appendix D. Model data

This section of the [Appendix](#) displays the key financial and technical assumptions that have been used for this study. For a more detailed description of all relevant input data, please refer to Ref. [73].

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 & Luxembourg	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

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	Solar PV	Wind Onshore	Wind Offshore	Total
France	251.8	381.7	133.7	767.2
Germany	200.4	222.6	83.6	506.6
Greece	62.8	105.6	27.6	196.0
Iberia	256.7	417.9	71.7	746.3
Italy	159.9	190.2	77.7	427.8
Netherlands	31.8	23.6	57.1	112.5
Poland	134.4	193.9	40.7	369.0
Scandinavia	62.3	197.4	420.4	680.1
Switzerland	18.7	20.8	0	39.5
United Kingdom	212.2	268.8	364.6	845.6
Total	1865.2	2774.2	1632.2	6271.6

Source: Gerbaulet and Lorenz [88].

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

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

*Source: European Commission et al. [89], Gerbaulet and Lorenz [88], and Ram et al. [90].

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

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

Source: European Commission et al. [89].

Input fuel efficiency for common conventional power plants.

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

Source: European Commission et al. [89].

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 [91], Booz & Company [92].

Yearly electricity demand per region in TWh.

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

Source: Gerbaulet and Lorenz [88].

Appendix E. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.esr.2019.100422>.

References

- [1] G. Plessmann, P. Blechinger, How to Meet EU GHG Emission Reduction Targets? A Model Based Decarbonization Pathway for Europe's Electricity Supply System until 2050, Technical Report, Reiner Lemoine Institute, Berlin, Germany, 2016.
- [2] J. Farfan, C. Breyer, Aging of European power plant infrastructure as an opportunity to evolve towards sustainability, *Int. J. Hydrogen Energy* 42 (2017) 18081–18091, <https://doi.org/10.1016/j.ijhydene.2016.12.138>. <https://linkinghub.elsevier.com/retrieve/pii/S0360319917300010>.
- [3] I. Boie, C. Kost, S. Bohn, M. Agsten, P. Bretschneider, O. Snigovyi, M. Pudlik, M. Ragwitz, T. Schlegl, D. Westermann, Opportunities and challenges of high renewable energy deployment and electricity exchange for north africa and europe – scenarios for power sector and transmission infrastructure in 2030 and 2050, *Renew. Energy* 87 (2016) 130–144, <https://doi.org/10.1016/j.renene.2015.10.008>. <https://linkinghub.elsevier.com/retrieve/pii/S096014811530361X>.
- [4] M.Z. Jacobson, M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M. A. Cameron, C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S. N. Fobi, O.K. Goldstrom, E.M. Hennessy, J. Liu, J. Lo, C.B. Meyer, S.B. Morris, K. R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world, *Joule* 1 (2017) 108–121, <https://doi.org/10.1016/j.joule.2017.07.005>. <http://www.sciencedirect.com/science/article/pii/S2542435117300120>.
- [5] European Environment Agency (EEA), Share of renewable energy in gross final energy consumption. https://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=t2020_31&plugin=1, 2018.
- [6] Council of the European Union, Intended Nationally Determined Contribution of the EU and its Member States, Council of the European Union, Riga, 2015. Technical Report, <http://www4.unfccc.int/ndcregistry/PublishedDocuments/Belgium%20First/LV-03-06-EU%20INDC.pdf>.
- [7] N. Johnson, V. Krey, D.L. McCollum, S. Rao, K. Riahi, J. Rogelj, Stranded on a low-carbon planet: implications of climate policy for the phase-out of coal-based power plants, *Technol. Forecast. Soc. Chang.* 90 (2015) 89–102, <https://doi.org/10.1016/j.techfore.2014.02.028>. <http://linkinghub.elsevier.com/retrieve/pii/S0040162514000924>.
- [8] B. Caldecott, J. McDaniels, Stranded Generation Assets: Implications for European Capacity Mechanism, Energy Markets and Climate Policy, Technical Report Working Paper, Smith School of Enterprise and the Environment, University of Oxford, 2014. <http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/StrandedGenerationAssets-WorkingPaper-FinalVersion.pdf>.
- [9] K. Bond, 2020 Vision: Why You Should See Peak Fossil Fuels Coming, Technical Report, Carbon Tracker Initiative, 2018. <https://www.carbontracker.org/reports/2020-vision-why-you-should-see-the-fossil-fuel-peak-coming/>.
- [10] D. Tong, Q. Zhang, Y. Zheng, K. Caldeira, C. Shearer, C. Hong, Y. Qin, S.J. Davis, Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target, *Nature* (2019), <https://doi.org/10.1038/s41586-019-1364-3>. <http://www.nature.com/articles/s41586-019-1364-3>.
- [11] B. Caldecott (Ed.), Stranded Assets and the Environment: Risk, Resilience and Opportunity, 1 ed., Routledge, 2018 <https://doi.org/10.4324/9781315651606>.

- [12] B. Caldecott, N. Howarth, P. McSharry, Stranded Assets in Agriculture: Protecting Value from Environment-Related Risks, Report, Smith School of Enterprise and the Environment, University of Oxford, Oxford, United Kingdom, 2013.
- [13] Carbon Tracker Initiative, Terms List, 2019. <https://www.carbontracker.org/refs-and-resources/terms-list/>.
- [14] Carbon Tracker Initiative, The \$2 Trillion Stranded Assets Danger Zone: How Fossil Fuel Firms Risk Destroying Investor Returns, Synthesis Report, Carbon Tracker Initiative, London, United Kingdom, 2015.
- [15] J.-F. Mercure, H. Pollitt, J.E. Viñuales, N.R. Edwards, P.B. Holden, U. Chewprecha, P. Salas, I. Sognnaes, A. Lam, F. Knobloch, Macroeconomic impact of stranded fossil fuel assets, *Nat. Clim. Chang.* 8 (2018) 588–593, <https://doi.org/10.1038/s41558-018-0182-1>.
- [16] C. McGlade, C. Ekins, The geographical distribution of fossil fuels unused when limiting global warming to 2 °C, *Nature* 517 (2015) 187–190, <https://doi.org/10.1038/nature14016>. <http://www.nature.com/nature/journal/v517/n7533/full/nature14016.html>.
- [17] M. Schneider, A. Froggatt, P. Johnstone, A. Stirling, T. Katsuta, M.V. Ramana, C. von Hirschhausen, B. Wealer, A. Stienne, J. Hazemann, World Nuclear Industry Status Report 2018, Technical Report, Mycle Schneider Consulting, Paris, 2018.
- [18] C. Kemfert, T. Burandt, K. Hainsch, K. Löffler, P.-Y. Oei, C. von Hirschhausen, Nuclear power unnecessary for climate protection—there are more cost-efficient alternatives, *DIW Econ. Bull.* 7 (2017) 498–506. http://www.diw.de/documents/publikationen/73/diw_01.c.572291.de/diw_econ_bull_2017-48-2.pdf.
- [19] J. Rogelj, D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, H. Kheshgi, S. Kobayashi, E. Kriegler, L. Mundaca, R. Séférián, M. Vilarino, Mitigation pathways compatible with 1.5 °C in the context of sustainable development, in: V. Masson-Delmotte, P. Zhai, D. Pörtner, H. O. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. Matthews, Y. Chen, M. Zhou, X. Gao, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (Eds.), Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, IPCC, 2018.
- [20] Eurostat, Eurostat Data Explorer, 2018. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_113a. (Accessed 13 September 2018).
- [21] O. Dessens, G. Anandarajah, A. Gambhir, Limiting global warming to 2 °C: what do the latest mitigation studies tell us about costs, technologies and other impacts? *Energy Strat. Rev.* 13–14 (2016) 67–76, <https://doi.org/10.1016/j.esr.2016.08.004>. <https://linkinghub.elsevier.com/retrieve/pii/S2211467X16300359>.
- [22] A. Pfeiffer, R. Millar, C. Hepburn, E. Beinhöcker, The '2 °C capital stock' for electricity generation: committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy, *Appl. Energy* 179 (2016) 1395–1408, <https://doi.org/10.1016/j.apenergy.2016.02.093>.
- [23] C. Hickey, P. Deane, C. McInerney, B. Ó Gallachóir, Is there a future for the gas network in a low carbon energy system? *Energy Policy* 126 (2019) 480–493, <https://doi.org/10.1016/j.enpol.2018.11.024>.
- [24] IRENA, Stranded Assets and Renewables: How the Energy Transition Affects the Value of Energy Reserves, Buildings and Capital Stock, Working Paper, International Renewable Energy Agency (IRENA), Abu Dhabi, 2017.
- [25] G. Wynn, The Dutch Coal Mistake: How Three Brand-New Power Plants in the Netherlands Are at Risk Already of Becoming Stranded Assets, Technical Report, Institute for Energy Economics and Financial Analysis, USA, 2016.
- [26] C.T. Initiative, Here Comes the Sun (And Wind), Report, Carbon Tracker Initiative, London, United Kingdom, 2019.
- [27] L.M. Fitzgerald, I. Braunger, H. Brauers, Destabilisation of Sustainable Energy Transformations: Analysing Natural Gas Lock-In in the Case of Germany, STEPS Centre, 2019. <https://opendocs.ids.ac.uk/opendocs/handle/123456789/14499>. <https://doi.org/10.1080/01436597.2017.1387477>.
- [28] K. Bos, J. Gupta, Climate change: the risks of stranded fossil fuel assets and resources to the developing world, *Clim. Change* 39 (2018) 436–453, <https://doi.org/10.1080/01436597.2017.1387477>.
- [29] J. Green, P. Newman, Disruptive innovation, stranded assets and forecasting: the rise and rise of renewable energy, *J. Sustain. Financ. Invest.* 7 (2017) 169–187, <https://doi.org/10.1080/20430795.2016.1265410>.
- [30] C. Gerbaulet, C. von Hirschhausen, C. Kemfert, C. Lorenz, P.-Y. Oei, European electricity sector decarbonization under different levels of foresight, *Renew. Energy* 141 (2019) 973–987, <https://doi.org/10.1016/j.renene.2019.02.099>.
- [31] I. Keppo, M. Strubegger, Short term decisions for long term problems – the effect of foresight on model based energy systems analysis, *Energy* 35 (2010) 2033–2042, <https://doi.org/10.1016/j.energy.2010.01.019>.
- [32] F. Fusco Nerini, I. Keppo, N. Strachan, Myopic decision making in energy system decarbonisation pathways. A UK case study, *Energy Strat. Rev.* 17 (2017) 19–26, <https://doi.org/10.1016/j.esr.2017.06.001>.
- [33] K. Hansen, C. Breyer, H. Lund, Status and perspectives on 100% renewable energy systems, *Energy* 175 (2019) 471–480, <https://doi.org/10.1016/j.energy.2019.03.092>. <https://linkinghub.elsevier.com/retrieve/pii/S0360544219304967>.
- [34] D. Bogdanov, J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A. S. Oyewo, L. de Souza Noel Simas Barbosa, C. Breyer, Radical transformation pathway towards sustainable electricity via evolutionary steps, *Nat. Commun.* 10 (2019) 1077, <https://doi.org/10.1038/s41467-019-08855-1>.
- [35] B. Heard, B. Brook, T. Wigley, C. Bradshaw, Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems, *Renew. Sustain. Energy Rev.* 76 (2017) 1122–1133, <https://doi.org/10.1016/j.rser.2017.03.114>. <https://linkinghub.elsevier.com/retrieve/pii/S1364032117304495>.
- [36] T. Brown, T. Bischof-Niemz, K. Blok, C. Breyer, H. Lund, B. Mathiesen, Response to 'Burden of proof: a comprehensive review of the feasibility of 100% renewable-electricity systems', *Renew. Sustain. Energy Rev.* 92 (2018) 834–847, <https://doi.org/10.1016/j.rser.2018.04.113>. <https://linkinghub.elsevier.com/retrieve/pii/S1364032118303307>.
- [37] E. Pursiheimo, H. Holtinen, T. Koljonen, Inter-sectoral effects of high renewable energy share in global energy system, *Renew. Energy* 136 (2019) 1119–1129, <https://doi.org/10.1016/j.renene.2018.09.082>. <https://linkinghub.elsevier.com/retrieve/pii/S096014811831156X>.
- [38] Y.Y. Deng, K. Blok, K. van der Leun, Transition to a fully sustainable global energy system, *Energy Strat. Rev.* 1 (2012) 109–121, <https://doi.org/10.1016/j.esr.2012.07.003>. <https://linkinghub.elsevier.com/retrieve/pii/S2211467X12000314>.
- [39] M. Child, O. Koskinen, L. Linnanen, C. Breyer, Sustainability guardrails for energy scenarios of the global energy transition, *Renew. Sustain. Energy Rev.* 91 (2018) 321–334, <https://doi.org/10.1016/j.rser.2018.03.079>.
- [40] F. Fusco Nerini, J. Tomei, L.S. To, I. Bisaga, P. Parikh, M. Black, A. Borrión, C. Spataru, V. Castán Broto, G. Anandarajah, B. Milligan, Y. Mulugetta, Mapping synergies and trade-offs between energy and the sustainable development goals, *Nat. Energy* 3 (2018) 10–15, <https://doi.org/10.1038/s41560-017-0036-5>.
- [41] D.L. McCollum, L.G. Echeverri, S. Busch, S. Pachauri, S. Parkinson, J. Rogelj, V. Krey, J.C. Minx, M. Nilsson, A.-S. Stevance, K. Riahi, Connecting the sustainable development goals by their energy inter-linkages, *Environ. Res. Lett.* 13 (2018), 033006, <https://doi.org/10.1088/1748-9326/aaaf3c>.
- [42] P.-Y. Oei, R. Mendelevitch, European scenarios of CO2 infrastructure investment until 2050, *Energy J.* 37 (2016), <https://doi.org/10.5547/01956574.37.SI3.poei>. <http://www.iaee.org/en/publications/ejarticle.aspx?id=2833>.
- [43] F. Steinke, P. Wolfrum, C. Hoffmann, Grid vs. storage in a 100% renewable Europe, *Renew. Energy* 50 (2013) 826–832, <https://doi.org/10.1016/j.renene.2012.07.044>. <https://linkinghub.elsevier.com/retrieve/pii/S0960148112004818>.
- [44] P. Capros, L. Paroussos, P. Fragkos, S. Tsani, B. Boitier, F. Wagner, S. Busch, G. Resch, M. Blesl, J. Bollen, Description of models and scenarios used to assess European decarbonisation pathways, *Energy Strat. Rev.* 2 (2014) 220–230, <https://doi.org/10.1016/j.esr.2013.12.008>. <https://linkinghub.elsevier.com/retrieve/pii/S2211467X13001065>.
- [45] D. Connolly, H. Lund, B. Mathiesen, Smart Energy Europe: the technical and economic impact of one potential 100% renewable energy scenario for the European Union, *Renew. Sustain. Energy Rev.* 60 (2016) 1634–1653, <https://doi.org/10.1016/j.rser.2016.02.025>. <https://linkinghub.elsevier.com/retrieve/pii/S1364032116002331>.
- [46] M. Child, C. Kemfert, D. Bogdanov, C. Breyer, Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe, *Renew. Energy* 139 (2019) 80–101, <https://doi.org/10.1016/j.renene.2019.02.077>.
- [47] Europe beyond coal, European Coal Plant Database, 2018. <https://beyond-coal.eu/data/>.
- [48] European Commission, Energy datasheets, EU28 Countries, European Commission, 2018. Technical Report, <https://ec.europa.eu/energy/en/data-analysis/country>.
- [49] European Union, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC (Text with EEA Relevance) 52, 2009, pp. 16–62, <https://doi.org/10.3000/17252555.L.2009.140.eng>. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0028>.
- [50] European Commission, Regulation (eu) 2018/842 of the European parliament and of the council of 30 may 2018 on binding annual greenhouse gas emission reductions by member states from 2021 to 2030 contributing to climate action to meet commitments under the paris agreement and amending regulation (eu) no 525/2013 (text with eea relevance), *Off. J. Eur. Union* 61 (2018) 26–42.
- [51] UNFCCC, Adoption of the Paris Agreement, 2015. Technical Report, United Nations Framework Convention on Climate Change, Paris, <https://unfccc.int/resour/resour/docs/2015/cop21/eng/109r01.pdf>.
- [52] France, Belgium, Denmark, Luxembourg, Netherlands, Portugal, Spain, Sweden Non paper on climate for the future of Europe, *Off. J. Eur. Union* (2019), <https://www.permanentrepresentations.nl/documents/publications/2019/05/08/non-paper-on-climate-for-the-future-of-europe>.
- [53] Portugal, France, Spain, European Commission EIB, Non Paper on Climate for the Future of Europe, Second Energy Interconnections Summit, 2018, https://ec.europa.eu/info/sites/info/files/lisbon_declaration_energyinterconnections_final.pdf.
- [54] S. Morgan, Eu Climate Deal Falls at Summit, Four Countries Wield the Axe, Euractiv, 2019. <https://www.euractiv.com/section/climate-strategy-2050/news/eu-climate-deal-falls-at-summit-four-countries-wield-the-axe/>.
- [55] Climate Action Network Europe, Off Target - Ranking of EU Countries' Ambition and Progress in Fighting Climate Change, Technical Report, Climate Action Network Europe, 2018. Brussels, Belgium, <http://www.caneurope.org/docman/climate-energy-targets/3357-off-target-ranking-of-eu-countries-ambition-and-progress-in-fighting-climate-change/file>.
- [56] Clean Energy Wire, Germany Set to Widely Miss Climate Targets, Env Ministry Warns, 2017. <https://www.cleanenergywire.org/news/germany-set-widely-miss-climate-targets-env-ministry-warns>.
- [57] T. Spencer, R. Pierfederici, O. Sartor, N. Berghmans, S. Samadi, M. Fischedick, K. Knoop, S. Pye, P. Criqui, S. Mathy, P. Capros, P. Fragkos, M. Bukowski, A. Śniegocki, M. Rosa Viridis, M. Gaeta, K. Pollier, C. Cassisa, Tracking sectoral progress in the deep decarbonisation of energy systems in Europe, *Energy Policy* 110 (2017) 509–517, <https://doi.org/10.1016/j.enpol.2017.08.053>.

- [58] Ecologic Institute, Climate, Planning for Net Zero: Assessing the Draft National Energy and Climate Plans, European Climate Foundation, The Hague, Netherlands, 2019. Technical Report, <https://www.ecologic.eu/16573>.
- [59] ENTSO-E, Statistical Factsheet, Provisional Values as of 4 May 2018, ENTO-E AISBL, Brussels, Belgium, 2017, 2018.
- [60] Central European Energy Partners, Gas Is Getting a Bigger Role in Power Generation in Poland, 2019. <https://www.ceep.be/gas-is-getting-a-bigger-role-in-power-generation-in-poland/>.
- [61] Smart Energy International, UK Combined Cycle Plant Approved, 2019. <https://www.smart-energy.com/industry-sectors/business-finance-regulation/uk-combined-cycle-plant-gas-turbine/>.
- [62] K. Hainsch, T. Burandt, C. Kemfert, K. Löffler, P.-Y. Oei, C. von Hirschhausen, Emission Pathways towards a Low-Carbon Energy System for Europe - a Model-Based Analysis of Decarbonization Scenarios, DIW Berlin, Discussion Paper 1745, https://www.diw.de/documents/publikationen/73/diw_01.c.594116.de/dp1745.pdf, 2018.
- [63] ECA, Improving the Security of Energy Supply by Developing the Internal Energy Market: More Efforts Needed, Special Report, European Court of Auditors, Luxembourg, 2015.
- [64] C.v. Hirschhausen, C. Gerbaulet, C. Kemfert, C. Lorenz, P.-Y. Oei (Eds.), Energiewende "Made in Germany": Low Carbon Electricity Sector Reform in the European Context, Springer International Publishing, 2018. <https://www.springer.com/de/book/9783319951256>.
- [65] B. der Justiz und für Verbraucherschutz (BMJV), Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2017), 2014. https://www.gesetze-im-internet.de/eeg_2014/.
- [66] BMWi, Erneuerbare Energien, 2018. <https://www.bmw.de/Redaktion/DE/Dossier/erneuerbare-energien.html>. (Accessed 13 September 2018).
- [67] P.-Y. Oei, Greenhouse gas emission reductions and the phasing-out of coal in Germany, in: C. von Hirschhausen, C. Gerbaulet, C. Kemfert, C. Lorenz, P.-Y. Oei (Eds.), Energiewende "Made in Germany", Springer International Publishing, Cham, 2018, pp. 81–116, https://doi.org/10.1007/978-3-319-95126-3_4. http://link.springer.com/10.1007/978-3-319-95126-3_4.
- [68] T. Haas, Die politische Ökonomie der Energiewende, Springer Fachmedien Wiesbaden, Wiesbaden, 2017, <https://doi.org/10.1007/978-3-658-17319-7>. <http://link.springer.com/10.1007/978-3-658-17319-7>.
- [69] G. Kungl, F.W. Geels, Sequence and alignment of external pressures in industry destabilisation: understanding the downfall of incumbent utilities in the german energy transition (1998–2015), Environ. Innov. Soc. Transit. 26 (2018) 78–100, <https://doi.org/10.1016/j.eist.2017.05.003>. <http://linkinghub.elsevier.com/retrieve/pii/S2210422417300175>.
- [70] I. Cadoret, F. Padovano, The political drivers of renewable energies policies, Energy Econ. 56 (2016) 261–269, <https://doi.org/10.1016/j.eneco.2016.03.003>. <https://linkinghub.elsevier.com/retrieve/pii/S0140988316300408>.
- [71] D.K. Jonsson, B. Johansson, A. Månsson, L.J. Nilsson, M. Nilsson, H. Sonnsjö, Energy security matters in the EU energy roadmap, Energy Strat. Rev. 6 (2015) 48–56, <https://doi.org/10.1016/j.esr.2015.03.002>. <http://linkinghub.elsevier.com/retrieve/pii/S2211467X1500005X>.
- [72] K. Löffler, K. Hainsch, T. Burandt, P.-Y. Oei, C. Kemfert, C. von Hirschhausen, Designing a model for the global energy system—GENeSYS-MOD: an application of the open-source energy modeling system (OSeMOSYS), Energies 10 (2017) 1468, <https://doi.org/10.3390/en101468>. <http://www.mdpi.com/1996-1073/10/10/1468>.
- [73] T. Burandt, K. Löffler, K. Hainsch, GENeSYS-MOD v2.0 - Enhancing the Global Energy System Model, DIW Data Doc. 95 (2018).
- [74] IPCC, Climate Change 2014: Synthesis Report, IPCC, Geneva, Switzerland, 2014. Technical Report.
- [75] J.C. Minx, W.F. Lamb, M.W. Callaghan, S. Fuss, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W.d.O. Garcia, J. Hartmann, T. Khanna, D. Lenzi, G. Luderer, G. F. Nemet, J. Rogelj, P. Smith, J.L.V. Vicente, J. Wilcox, M.d.M.Z. Dominguez, Negative emissions—Part 1: research landscape and synthesis, Environ. Res. Lett. 13 (2018), 063001, <https://doi.org/10.1088/1748-9326/aabf9b>.
- [76] S. Fuss, W.F. Lamb, M.W. Callaghan, J. Hilaire, F. Creutzig, T. Amann, T. Beringer, W.d.O. Garcia, J. Hartmann, T. Khanna, G. Luderer, G.F. Nemet, J. Rogelj, P. Smith, J.L.V. Vicente, J. Wilcox, M.d.M.Z. Dominguez, J.C. Minx, Negative emissions—Part 2: costs, potentials and side effects, Environ. Res. Lett. 13 (2018), 063002, <https://doi.org/10.1088/1748-9326/aabf9f>.
- [77] A. Matthey, B. Bünger, Methodological Convention 3.0 for the Assessment of Environmental Costs - Cost Rates, Umweltbundesamt, Dessau-Roßlau, Germany, 2019. Version 02/2019, Technical Report, <https://www.umweltbundesamt.de/publikationen/methodological-convention-30-for-the-assessment-of>.
- [78] finanzen.net, CO₂ European Emission Allowances - Commodity Price (06.08.2019), 2019. <https://markets.businessinsider.com/commodities/co2-european-emission-allowances>.
- [79] H. Graupner, German Government Approves Nuclear Phaseout Compensation, Deutsche Welle, 2018. <https://www.dw.com/en/german-government-approves-nuclear-phaseout-compensation/a-43892394>.
- [80] BMWi, Abschlussbericht Kommission "Wachstum, Strukturwandel und Beschäftigung", 2019. Technical Report, Berlin, https://www.kommission-wsb.de/WSB/Redaktion/DE/Downloads/abschlussbericht-kommission-wachstum-strukturwandel-und-beschaeftigung.pdf?__blob=publicationFile&v=4.
- [81] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kyproos, A. Hughes, S. Silveira, J. DeCarolus, M. Bazillian, A. Roehrl, OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development, Energy Policy 39 (2011) 5850–5870, <https://doi.org/10.1016/j.enpol.2011.06.033>. <http://www.sciencedirect.com/science/article/pii/S0301421511004897>.
- [82] International Energy Agency, Electricity Information 2018, International Energy Agency, Paris, France, 2018 oCLC: 1078916161.
- [83] S. O. of the Republic of Serbia, Bulletin - Energy Balances 2015, Technical Report 622, Statistical Office of the Republic of Serbia, Belgrade, 2017. <http://publikacije.stat.gov.rs/G2017/PdfE/G20175622.pdf>.
- [84] Statistics Norway, Electricity balance Norway, 2017. <https://www.ssb.no/en/en-ergi-og-industri/statistikker/elektrisitet/aar>.
- [85] Swissgrid, Energy Statistic Switzerland 2015, 2015. Technical Report, Swissgrid, Aarau, Switzerland, <https://www.swissgrid.ch/dam/dataimport/energy-statistic/EnergieUebersichtCH-2015.xls>.
- [86] IEA, World Energy Balances 2018, World Energy Balances, International Energy Agency, Paris, France, 2018 oCLC: 1101392660.
- [87] OECD, CO₂ Emissions from Fuel Combustion 2017, OECD Publishing, Paris, 2017 oCLC: 1013820838, <http://public.eblib.com/choice/publicfullrecord.aspx?p=5160851>.
- [88] C. Gerbaulet, C. Lorenz, dynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market, Data Documentation No. 88, DIW Berlin, Berlin, Germany, 2017.
- [89] European Commission, Joint Research Centre, Institute for Energy and Transport, SERTIS, Energy Technology Reference Indicator (ETRI) Projections for 2010–2050, Technical Report, Publications Office of the European Union, Luxembourg, 2014.
- [90] M. Ram, D. Bogdanov, A. Aghahosseini, S. Oyewo, A. Gulagi, M. Child, C. Breyer, Global Energy System Based on 100% Renewable Energy - Power Sector, Lappeenranta University of Technology (LUT) and Energy Watch Group, Lappeenranta, Finland and Berlin, Germany, 2017. Technical Report.
- [91] IEA, World Energy Outlook 2016, OECD/IEA, Paris, France, 2016.
- [92] Booz & Company, Understanding Lignite Generation Costs in Europe, AEH, 2014. <https://www.dei.gr/documents2/investors/meleth%20booz/understanding%20lignite%20generation%20costs%20in%20europe.pdf>.