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Lessons from Modeling 100% Renewable Scenarios Using GENeSYS-MOD

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ABSTRACT

The main aim of models has never been to provide numbers, but insights. Still, challenges prevail for modelers to use the best configuration of their models to provide helpful insights. In the case of energy system modelling, this becomes even more complicated due to increasing complexity of the energy system transition through the potential and need for sector coupling. This paper therefore showcases specific characteristics and challenges for energy system modelling of 100% renewable scenarios. The findings are based on various applications and modifications of the framework GENeSYS-MOD examining different regional characteristics for high renewable configurations in the world, China, India, South-Africa, Mexico, Europe, Germany, and Colombia. The paper elaborates on our experiences of the last years of choosing the best, yet still computable, configuration of GENeSYS-MOD with respect to spatial and time resolution as well as sufficient detailed description of the energy system transition effects. The aim of this paper is therefore twofold, to better understand and interpret existing models as well as to improve future modeling exercises.

Keywords: Energy transition, Renewables, Modeling, Scenarios, Climate policy, Energy system

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1. INTRODUCTION

1.1 The Origin of 100 % Renewable Scenarios

As a means to combat climate change and stop global warming, scenarios with increasing shares of renewable energy have observed increasing attention with the beginning of the 21st century. When the first scenarios with 100% renewable energy supply were published, back in the 2000 years, they were generally considered as "out-of-the-box" thinking, if not completely utopic. This is highlighted by the scientific debate started by Jacobson et al. (2015). They presented an energy system purely based on wind, water, and solar for the United States and thus showing that a low-cost, reliable, renewable energy system is possible. Their results and

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assumptions were then highly criticized by Bistline und Blanford (2016) as well as Clack et al. (2017). In the following discussion, the team of Jacobson et al. presented a substantial rebuttal to their critics (compare Jacobson et al. (2016) and Jacobson et al. (2017)), but the discussion about the feasibility of 100% renewable energy systems is still ongoing. Loftus et al. (2015) criticize that most scenarios that exclude nuclear or carbon capture technologies need to be supplemented by more detailed analyses realistically addressing the key constraints on energy system transformation to provide helpful policy guidance. With more studies presenting possibilities of 100% renewable energy systems for different global regions, Heard et al. (2017) presented four criteria for assessing the feasibility of 100% scenarios. They conclude that for all of the 100% analyses feasibility has been insufficiently demonstrated. Contrary, this approach and result was again highly criticized by Brown et al. (2018). They, on the one hand, address all the concerns raised by Heard et al. (2017), and, furthermore, provide even further evidence for the feasibility of purely renewable based energy systems. Diesendorf and Elliston (2018), in a similar manner, elaborate on the feasibility of renewables providing the key requirements of reliability, security and affordability. They, on the other hand, identify political, institutional and cultural obstacles as main barriers for a 100% renewable system.

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

Overall, the discussion of 100% renewable scenarios shifted from general feasibility issues to specific assumptions. Studies analyzing the transformation of energy systems should also be aware of the biases and correctness of assumptions. Creutzig et al. (2017) show the underestimated potential of solar energy within the fifth assessment report of the IPCC due to underlying bias in the models. Also, as presented by Mohn (2019), the International Energy Agency's (IEA) World Energy Outlook (WEO) suffers from a status-quo bias in favor of fossil fuels and constantly underestimates the potential and development of renewable energy sources. This is especially important, as the WEO is an often-used data source for many energy system scenarios. A further analysis and comparison of different energy outlooks and scenarios is presented in this issue of EEEP by Ansari, Holz, and al-Kuhlani (this issue).

By the end of 2019, there are now numerous studies, which elaborate renewable energy scenarios using different models including sector coupling. Jenkins et al (2018) review and distill insights from 40 papers examining low carbon scenarios since 2014 including various articles showcasing 100% renewable scenarios. An even more comprehensive literature overview of in total 180 academic peer-reviewed papers since 2004 examining 100% renewable pathways can be shown in Hansen et al (2019). This is complemented through a recent special issue by the journal Energies comprising of 12 more papers on this topic by Kemfert et al. (2019). Also, within this EEEP symposium an article by Breyer et al. (this issue) examines the techno-economic benefits of global energy interconnection throughout high renewable scenario pathways.

Jacobsen et al. (2017), being one of the first elaborate studies, provide an extensive analysis of 100% renewable energy sources (RES) by 2050 of 139 countries. The results show that 100% RES is possible and can contribute to the (energy price) stability, the decline of unemployment and health related problems due to high pollution, and increase energy access because of decentralized RES. Its findings of the feasibility of a 100% RES scenario in that way supports assumptions made in this paper. Moreover, Löffler et al. (2017) conduct studies focusing on pathways until 2050 by using the energy system model GENeSYS-MOD and examining case studies (Hainsch et al. 2018; Lawrenz et al. 2018). Additionally, Ram et al. (2019) find out that a 100% RE pathway is globally feasible in all analyzed sectors (power, heat, transport and desalination) before 2050 using the Lappeenranta-Lahti University of Technology (LUT) energy system model. They further show that the sustainable energy system is more cost effective and efficient. Therefore, PV is also the main driver in terms of employment in the job calculation based on Ram, Aghahosseini, and Breyer (2019).

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

1.2 Research Focus

This paper showcases specific characteristics and challenges for energy system modelling of 100% renewable scenarios. The findings are based on various applications and modifications of the framework GENeSYS-MOD examining different regional characteristics for high renewable configurations. The main aim of models has never been to provide numbers, but insights (Huntington, Weyant, and Sweeney 1982)—still challenges prevail for modelers to use the best configuration of their models to actually provide helpful insights. This becomes even more complicated due to increasing complexity of the energy system transition through the potential and need for sector coupling as well as rising international connections. The following sections therefore elaborate on our experiences of the last years of choosing the best, yet still computable, configuration of GENeSYS-MOD (section 2) with respect to spatial (section 3) and temporal resolution (section 4) as well as sufficient detailed description of the energy system transition effects (section 5) and result interpretation (section 6). The aim of this paper is therefore twofold, to better understand and interpret existing models as well as to improve future modeling exercises.

2. METHODOLOGY

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

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

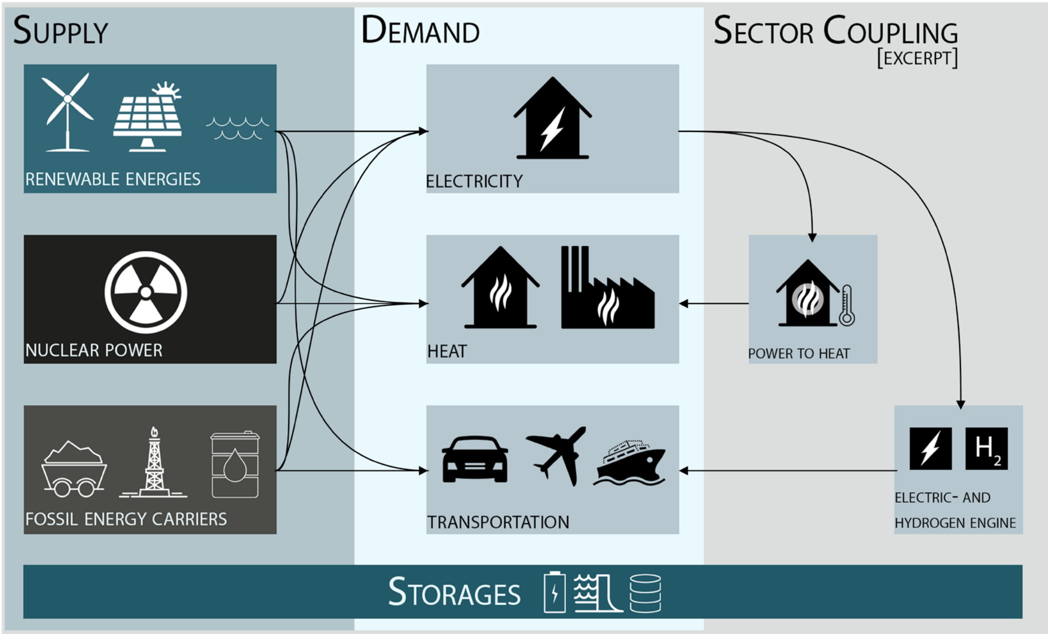

FIGURE 1
Description of GENeSYS-MOD.

2.2 Data Assumptions

Since the availability of wind and solar energy fluctuates with the weather conditions, a temporal and spatial balance is necessary in order to be able to cover the energy demand at any time. For this purpose, several technologies for storage and sector coupling are implemented in the model. Above all, lithium-ion batteries serve to balance temporal fluctuations in energy supply and demand. In addition, the coupling of the electricity sector with the transportation, heating and industrial sectors enables their decarbonization by using electricity from renewable sources. Spatially, the model in most applications comprises of 10-20 nodes, grouping together a number of smaller countries or regions. It is possible to exchange fuels and electricity between the regions, but not heat. In order to keep the complexity of the model calculable, aggregation is also carried out on a temporal level. In the course of the analysis, all hours of a year are summarized into time slices, which represent seasonal and daily fluctuations of demand and the availability of renewable energies.[1] The years 2020 to 2050 are considered in integrated five-year steps, assuming full knowledge of future developments in demand, costs, and availability of renewable energies. The calculations are mainly based on cost estimates from 2018; however, the results could underestimate the potential of renewables due to unexpected, rapid cost decreases in renewable energies as well as storage technologies. On the other hand, the calculations do not sufficiently consider a part of the integration costs of renewables due to the lower regional and temporal resolution, which leads to an overestimation of the potentials of fluctuating renewables.

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

The underlying cost assumptions can be found within an overall data documentation of GENeSYS-MOD (Burandt, Löffler, and Hainsch 2018). Country specific data is specified within the respective papers analyzing the world (Löffler et al. 2017), China (Burandt et al. 2019), Europe (Löffler et al. 2019), Germany (Bartholdtsen et al. 2019), India (Lawrenz et al. 2018), Mexico (Sarmiento et al. 2019), South-Africa (Hanto et al. 2020) and Colombia (Hanto et al. 2019).

3. CHOOSING THE BEST SPATIAL RESOLUTION

3.1 The Devil Lies within the Detail: Differences of a Continental, National and Regional Investigation

The devil lies within the detail as can be seen in our application of the framework GENeSYS-MOD to analyze 100% renewable pathways for the world (Löffler et al. 2017), Europe (Löffler et al. 2019), and Germany (Bartholdtsen et al. 2019) (see Figure 2). This becomes particularly apparent, when examining the distribution of different renewable technologies. The global analysis shows an even spread of wind on- and offshore and photovoltaics. A more detailed look at the European level, however, clarifies that some countries—mostly within Southern Europe—focus on photovoltaics. More northern countries, on the other hand, profit from high wind energy potential. Also, when looking in more detail at the evolvement over time, some countries—e.g. Poland—envision a much slower progress compared to other countries. This can be explained by very low starting values of renewables in 2015, which need more time to ramp up to high renewable shares in later periods. While these results might not be of big surprise to experts of the European energy system—they, however, explain the need for calibrating less spatially detailed linear models in a sufficient matter: a linear global model might otherwise choose to only invest in the cheapest renewable technology for each continent, not incorporating regional differences. Such model outcomes would in this case result in too simplified answers with little to no real insights. This can also be seen in papers by Hörsch and Brown (2017), Cao et al. (2018) and Hess et al. (2018) examining the role of spatial scale in joint optimisations of generation and transmission. They show trade-offs between better representation of transmission or distribution grid representation, exploitation of renewable sites and computational limitations for highly renewable scenarios.

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

3.2 The Energy Transition Can Result in the Shift of Energy Supply Centers

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

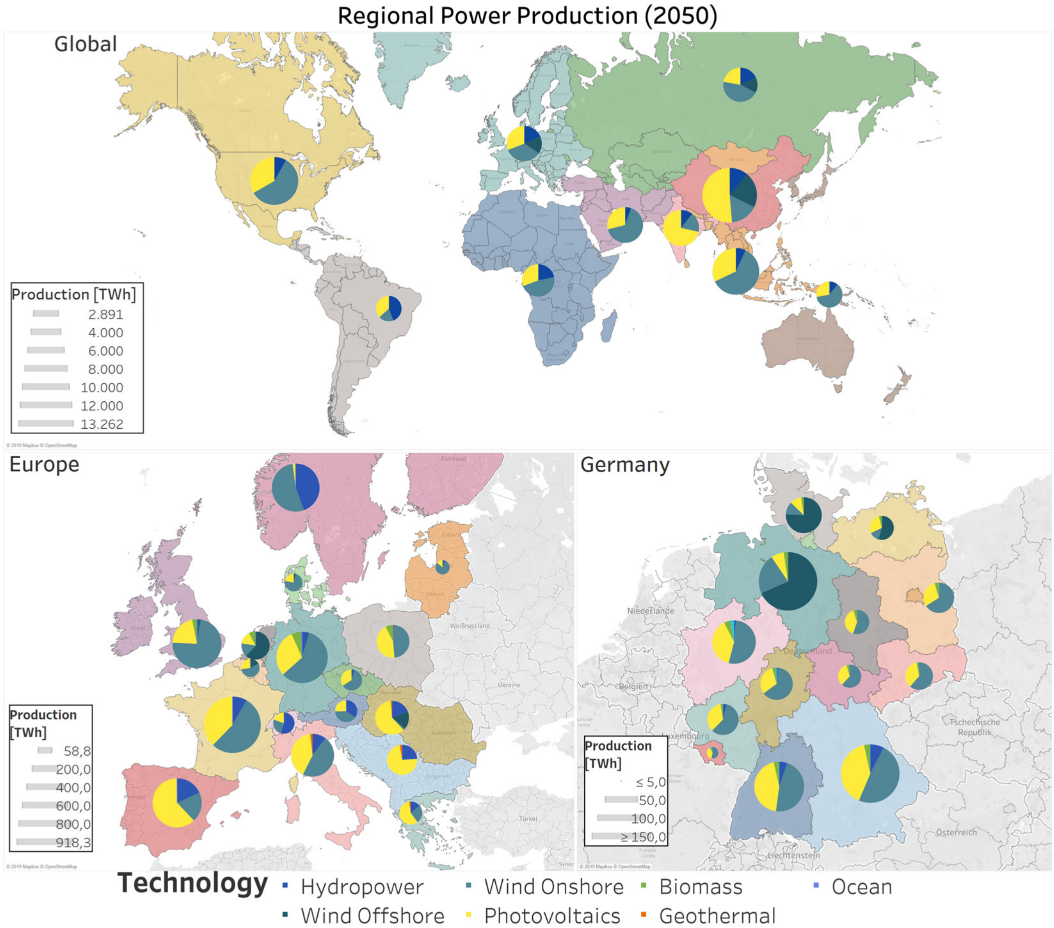

FIGURE 2

Scaling down 100% Renewable scenarios—for the World, Europe and Germany.

Source: Own illustration based on Löffler et al. (2017, 2019) and Bartholdtsen et al. (2019).

renewable potential sites might be located in different regions. Extreme examples for this were examined by us within South Africa (Hanto et al. 2020) and China (Burandt et al. 2019).

In South-Africa, in 2015 coal mining as well as the production of electricity concentrates in Mpumalanga as illustrated in Figure 3. Within a high renewable scenario by 2050 this role of the biggest power producers shifts to regions like Northern Cape, Eastern Cape, and Free State (Hanto et al. 2020). Similar results can be seen within the case study on China (Burandt et al. 2019): Being a region with high irradiation, Inner Mongolia will become the dominant power-generating province in China. This will require substantial grid extension measures (nearly doubling the total power transmission capacity from 2020 until 2050). On a positive note, the large regional extension of China enables the regional power trade to balance out the variability of renewables. Also, the regional disparity in the availability of biomass results in a significant increase in biomass, hydrogen, biogas, and synthetic methane trading.

Such configurations are presented as cost-optimal from a central omniscient planners' perspective. The implied needed investment costs for the electricity transmission and distribution grid (Breyer et al. this issue), however, underestimate difficulties and transaction costs for the construction of such enormous infrastructure within such short time and therefore deserve further research. Incorporating additional transaction costs, e.g. to increase public acceptance for the construction of new transmission lines, or including local preferences for keeping existing power production centers, might instead result in more realistic projections.

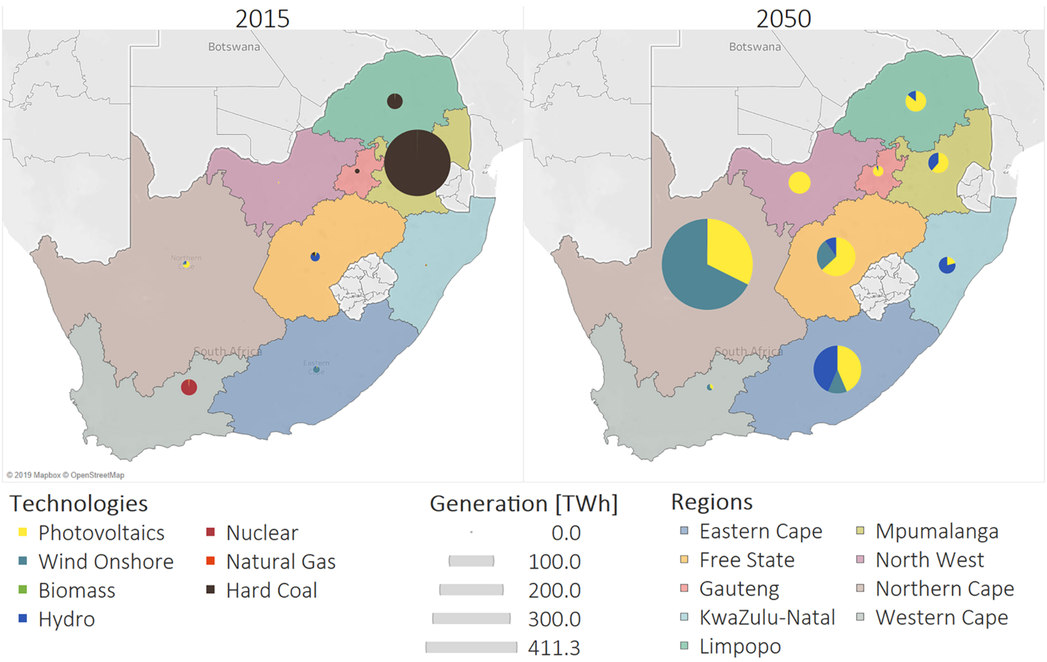

FIGURE 3

Change of regional power production—in South Africa.

Source: Own illustration.

4. TEMPORAL ASPECTS OF MODELING

4.1 Improving the Time Resolution

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

The effect of applying different time resolutions can be seen within sensitivity runs of our case study on China, see Burandt et al. (2019). We analyze decarbonization pathways of the

Chinese energy system comparing different hourly resolutions. The sensitivity scenario calculating every 73^{rd} hour with ramping constraints was used as a baseline. As shown in this Figure 4, the reduction from every 73^{rd} to every 25^{th} hour for the selection of the final time-series does not significantly impact the results, especially in the first years of the modeled periods. Deactivation or activation of the newly added ramping equations (compare Burandt el al. (2019) for a detailed description of the equations), on the other hand, has a bigger influence on the results. For the annual power production, a decrease of natural-gas usage in the later model periods can be observed when the ramping constraints are deactivated. Also, removing these constraints leads to a prolonged relevance of coal in the power system. Without ramping constraints, coal can be used in the model as a flexible power generation to balance intermittent variable renewable energy sources alongside storages, although coal-fired power plants often have only limited cycling and ramping capabilities in the real world.

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

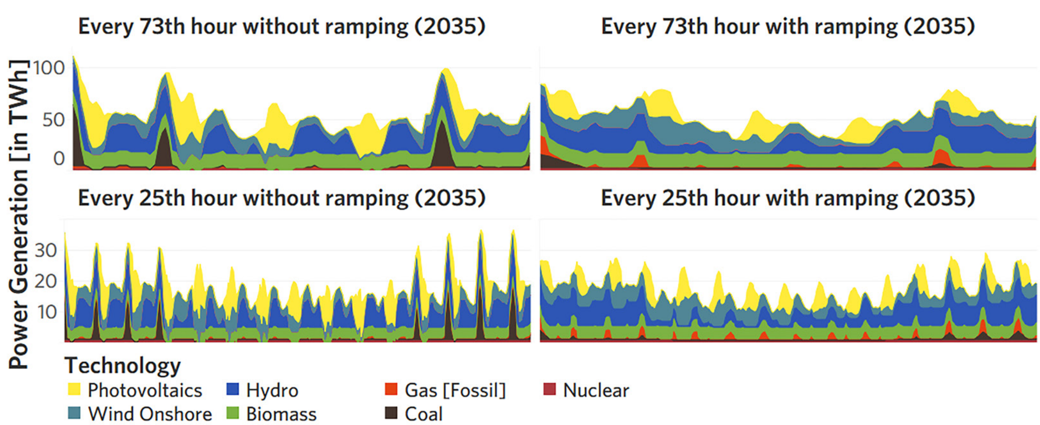

FIGURE 4

Effects of more detailed temporal resolution in comparison to better technical representation of ramping.

Source: Adapted from Burandt et al. (2019).

4.2 Effects of Reduced Foresight on Energy Pathways

One crucial feature of most large-scale energy system models is that they operate under the assumption of perfect foresight. This is valid both for intra-year data (see chapter 4.1), as well as for the pathway computation. The model therefore already “knows” about all impacts and costs that would occur for each possible decision and tends to choose the cost-optimal pathway from the viewpoint of an omniscient social planner.

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

Löffler et al. (2019) analyze this discrepancy between theoretical socially cost-optimal pathways and those, that would occur when foresight into future action is limited. For this, they introduce two new scenarios to their European model—both featuring myopic (reduced) foresight. Figure 5 shows the differences between the *BASE* scenario, one including reduced foresight (*RED*) and one that additionally introduces political boundaries and barriers (*POL*).

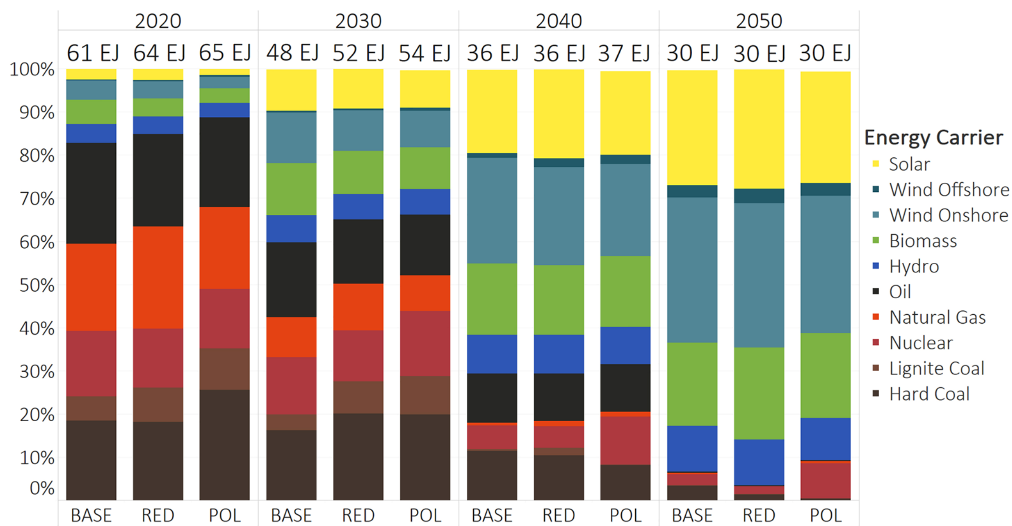

FIGURE 5

Primary energy supply, both relative, as well as total amount in Exajoule (EJ)—for Europe.

Source: Adapted from Löffler et al. (2019).

Clear differences can be observed: coal-based technologies see an increased use in the near to intermediate future, at the cost of the growth of RES when reduced foresight is included. Interestingly enough though, since all scenarios are required to adhere to the 2°C goal, the *RED* and *POL* scenarios actually need a steeper emission reduction path in the later years. This comes with significant cost increases, as well as massive amounts of stranded capacities (see Figure 6) and technical challenges for a faster ramp up of some technologies only in the 2040s. Also, such steeper transformations in the 2040s might result in higher societal challenges or even structural breaks endangering the aimed at just transition. Another interesting approach by Heuberger et al. (2017) considers the effect of including endogenous technology cost learning to improve optimal capacity expansion planning.

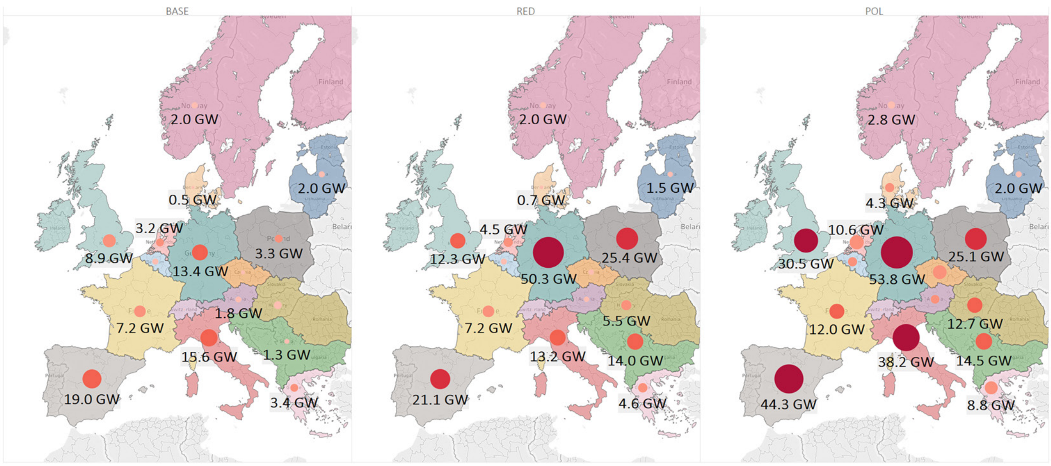

FIGURE 6

Total stranded assets for coal- and gas-fueled power generation in the year 2035—across Europe.

Source: Adapted from Löffler et al. (2019).

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

5. MORE DETAILED ANALYSIS OF SECTORAL TRANSITIONS

5.1 Examining the Industry Sector More Closely

For assessing the potential impact of sector-coupling on the development of an energy system, a detailed sectoral representation also of the industry sector is needed as seen within works of Lechtenböhmer et al. (2016), Vogl et al. (2018), and Fleiter et al. (2018). Currently, only limited technologies that allow direct electrification of high-temperature industry processes (e.g., steel, aluminum, or cement production) are available or still need fossil feedstock. Therefore, the distinct inclusion of such processes in energy system models is needed for assessing ambitious decarbonization scenarios. Especially for China, whose energy-intense high-temperature industry is of high importance, the explicit representation of different industrial sectors is needed for generating thoughtful insights. Therefore, Burandt et al. (2019) altered the preexisting structure of high-temperature and low-temperature heat, as depicted in Löffler et al. (2017) and Burandt, Löffler, and Hainsch (2018). The new four different temperature ranges with allowing for a more distinct differentiation in industrial (0–100° C, 100–1000° C, and >1000° C) and residential heating (0–100° C).

Due to higher CO_2 abatement costs, it is only in the 100% renewable scenarios that coal is phased-out also within the industrial heat sector (see figure 7). This phase-out is accompanied by higher usage of gas- and biomass-based heating. In the second quarter of the century, hydrogen and geothermal play a more significant role. Nevertheless, a large degree of electrification is required, which is most cost- and emission-efficient when the power sector is already decarbonized. The examination of an optimal decarbonization share of individual sectors will therefore be examined more closely in the next section.

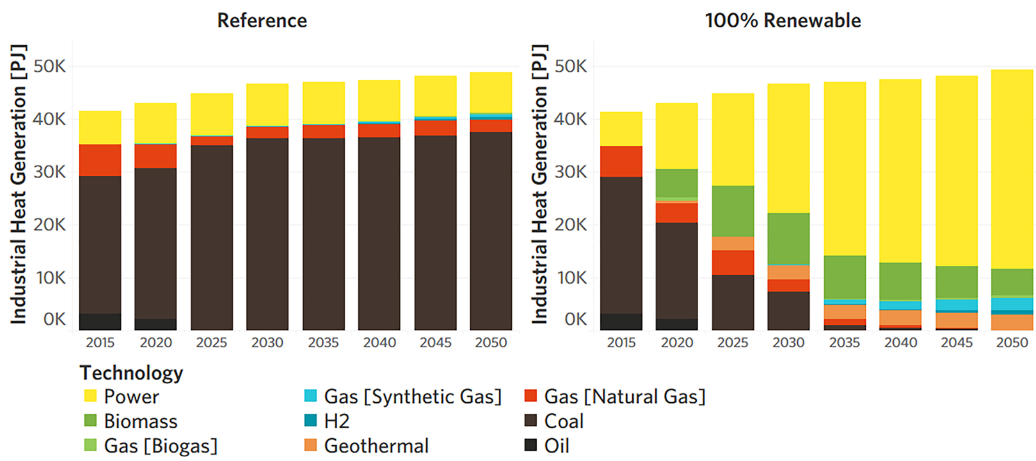

FIGURE 7
Decarbonization of industrial heat—in China.
Source: Adapted from Burandt et al. (2019).

5.2 What is an Optimal Share of Renewables for Each Sector

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

As a result, a cost curve that represents the relative change in costs can be obtained. This cost curve regularly takes the shape of a "U" (see figure 8), meaning that the integration of RES into the system first leads to (usually significant) cost savings, whereas towards 100% RES, the costs usually increase again. This is vastly different for the different sectors, with power and transport showing very high cost-optimal shares of renewables (75% and 90%, respectively), whereas the heating sector (especially when it comes to industrial process heat) experiences rather low shares (5% for the Mexican energy system). This is due to the inherent differences between the sectors, concerning the availability of RES-based technology options and their cost assumptions.

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

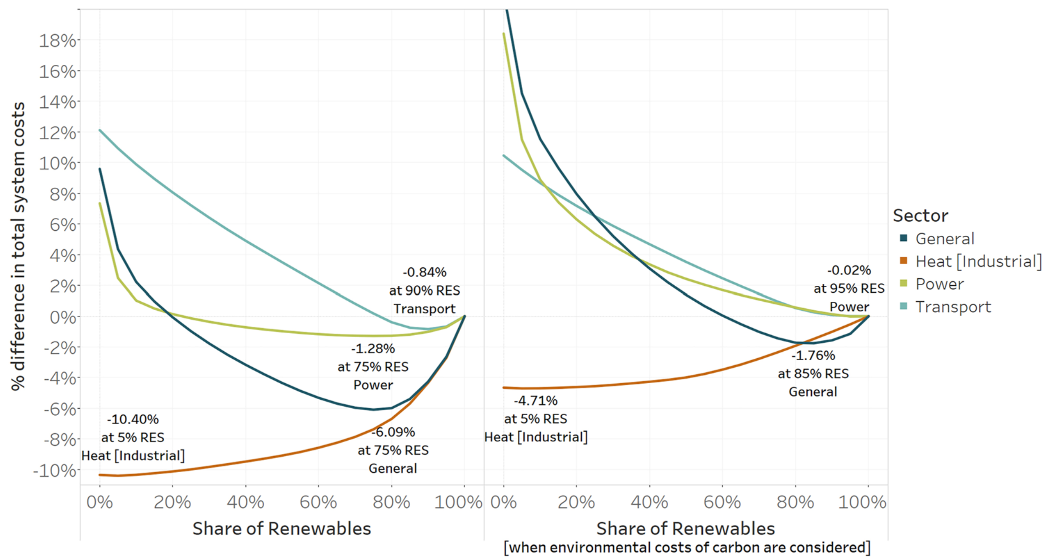

FIGURE 8

Calculating an optimal renewable share—for Mexico.

Source: Adapted from Sarmiento et al. (2019).

from 75% to 85%—with the power and transportation sectors achieving almost 100% RES as the cost-optimal shares.

5.3 Examining the Employment Potential of the Energy System Transition

Energy system models can help political decision makers to understand consequences of the transition not only for the technological energy system but also for the resulting employment effects as elaborated for South-Africa (Hanto et al. 2020) and Colombia (Hanto et al. 2019) in the following section.

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

Development of renewable energies will generate new employment opportunities along the entire supply chain (López et al. 2019). Job types differ in temporal occurrence as well as possible geographic location. Looking at the skill level, the relatively low needs for expertise in the operation and maintenance (O&M) in the PV sector are ideal to create jobs for former miners. For Colombia, permanent jobs in O&M triple from 2015 until 2050 in total and are mainly due to the build-up in PV power capacity and to a lesser extent due to additional hydropower capacity. Combined with the steadily rising job numbers for the Construction & Investment (C&I) and partial manufacturing of PV power stations, the total jobs, excluding the manufacturing side, significantly outnumber the coal mining job numbers of 2015.

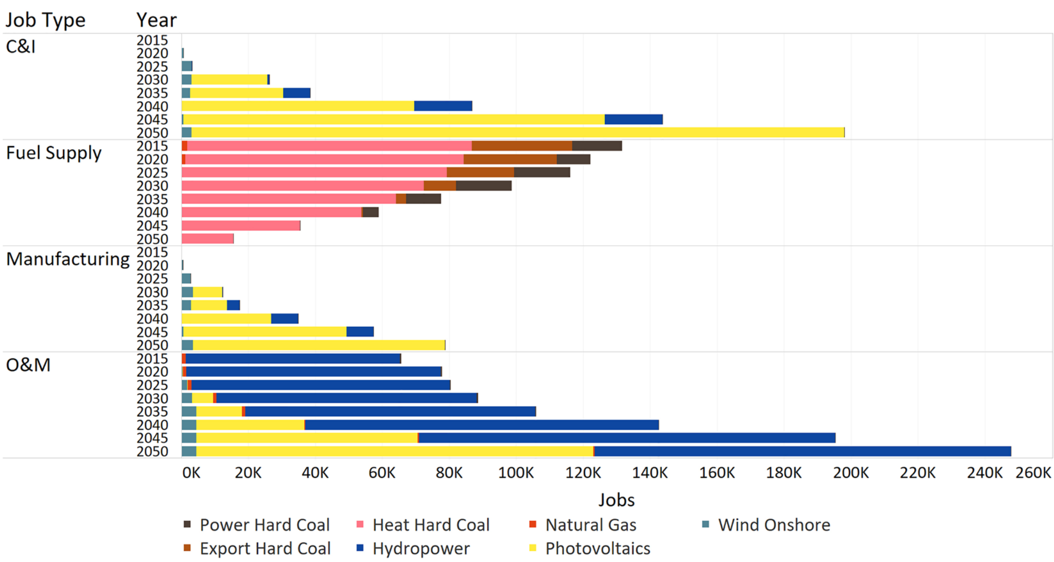

FIGURE 9
Employment effects for 100% renewable scenarios—in Colombia.
Source: Adapted from Hanto et al. (2020).

6. CONCLUSIONS

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

- Models largely depend on taken assumptions, including in particular the choice of data, sometimes having to be estimated far into the future. Applying discount factors for future costs and damages, as done by most models, hereby contradicts any principle of intergenerational justice concepts. Using a social discount rate instead, might provide different results for many modeling exercises.

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

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

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

Further inter- and transdisciplinary research is needed to accompany the upcoming energy system transition. From a modeling perspective this could be achieved through the (soft) coupling of energy system models with other models examining macro-economic effects (e.g.

cge-models) or behavioural aspects (esp. within the transport sector). However, also more qualitative works, e.g. on the political economy of fossil fuel phase-out, could be included in models through the inclusion of regional specific transition indicators. In addition, the effect of the energy system transition on the energy-food-nexus, the usage of rare earth materials or on other sustainable development goals would be of high interest for academia and society likewise.

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