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The Economics Of Decarbonizing Electricity Production

Gregor Schwerhoff

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Gregor Schwerhoff[*]

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ABSTRACT: Electricity production is the sector with the largest share of global emissions and there are many options for decarbonizing it. Identifying the lowest cost option for achieving decarbonization (and full reliability) is a complex optimization problem at the intersection of economics and engineering. Key determinants are the cost of individual technologies, the geographical potential, the complementarities between energy sources and supporting infrastructure like electricity grids and energy storage. This paper reviews the literature on the subject and draws high-level conclusions from the abundance of specialized analyses. It finds that energy-economy models have strongly changed projections of the optimal electricity mix in recent years. While the models differ in detail, models project that the share of renewable energy, mostly solar and wind power, increases steadily in a “below 2°C” scenario and becomes the dominant source of energy by 2050. An electricity system based on solar and wind power can use flexibility options as a complement instead of baseload energy. Models vary by the degree to which renewable energy is supported by carbon capture and storage, bioenergy, and nuclear energy.

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Author’s E-Mail Address:	gschwerhoff@imf.org

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[*] International Monetary Fund, gschwerhoff@imf.org

WORKING PAPERS

The economics of decarbonizing electricity production

Prepared by Gregor Schwerhoff

Contents

1. Introduction

Economists have a key role in providing policy advice for the energy transition. Their focus often is on designing policy instruments to promote low-carbon energy options. However, economists are increasingly confronted with questions on which energy sources will be used in a low-carbon world. A key aspect of decarbonizing energy use will be an increasing use of electricity and hence building a cost-effective and stable low-carbon electricity system. Electricity production generates a large share of global emissions, making the decarbonization of the electricity sector a macroeconomic policy priority. There is a large volume of analysis available at the intersection of climate and energy economics which provides insights on how electricity production can be decarbonized. However, the analysis is dispersed among many publications which contain only pieces of the puzzle.

This paper is designed to introduce general economists to the modeling of how the electricity system should evolve in order to decarbonize electricity systems. The main contribution of the paper is to put together the dispersed pieces of information from highly specialized research publications. It combines a brief introduction to relevant concepts with the latest research results on it. A second contribution is that it identifies commonalities and differences of state-of-the-art energy-economy models and explains them based on technological trends. Finally, the paper uniquely compares current model results with previous results to document and explain a major shift in results regarding optimal decarbonization strategies.

Solar and wind energy have emerged as those technologies with the lowest cost in terms of levelized cost of electricity (IRENA 2023; Way et al. 2022). However, solar and wind energy are intermittent, meaning that they are not continuously available due to factors that cannot be controlled. This raises the question of how much a country can rely on these technologies and which investments are needed to stabilize the electricity system. It can also be asked if alternatives, like carbon capture and storage (CCS), nuclear energy and biomass, could be superior options from a system perspective.

A key resource to project the future development of the electricity system are Integrated Assessment Models (IAMs).[1] They determine optimal electricity system designs based on cost, grid stability, emissions, and technology-specific technical potentials. These models are developed and refined in research institutes by teams of modelers over many years. The models receive government funding and regularly publish their results in peer-reviewed journals. In addition, the models are used in global assessments of the scientific consensus, like the reports of the Intergovernmental Panel on Climate Change (IPCC) and the Network for Greening the Financial System (NGFS). Recent IAM model results vary between models, scenarios, and geographical scope, but their results have important common features. First, the electricity production relies on a mix of technologies. Second, in scenarios that achieve temperature targets, the share of renewable energy increases over time until at least 2050 and becomes the dominant energy source over time. Third, the use of variable renewable energy (VRE), predominantly solar and wind energy, is complemented by flexibility options like network extension and energy storage. The first and third of these points emphasize that the models realistically reflect the complexity of the electricity system and acknowledge the complementarities required for a scale-up of solar and wind energy.

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[1] More specifically, this paper relies on process-based IAMs, which are typically used to provide emission scenarios for future climate change projections and to evaluate efficient mitigation strategies. This is different from cost-benefit IAMs that fully integrate a stylized socio-economic model with a reduced-form climate model. For more on types of IAMs, see https://www.iamconsortium.org/what-are-iams/.

The observation that IAMs identify solar and wind energy as the main options to expand electricity production is a very recent development. This paper shows that until recently, IAMs had a much larger share of CCS, nuclear energy, and biomass in projections for decarbonizing electricity production. This shows that the models allow, in principle, a large variety of decarbonization options. It also shows technology development in recent years has changed the outlook on future electricity production fundamentally. One driver of change is the price decline for solar and wind energy, which was not anticipated at this speed by experts. Another driver of change is the development of flexibility options. The cost of batteries has experienced a similar cost decline as the cost for solar and wind energy. In addition, the technology for many other flexibility options have become competitive.

The recent development of the research on energy systems provides two further insights. First, a combination of solar and wind energy is the best option for decarbonizing electricity in all world regions (while some countries can source a large part of electricity production from hydropower and geothermal energy as well). IAMs model between 11 and 32 world regions and reflect many specific features of the regions. The specific features include the location-specific potential for renewable energy and its variability, as well as the existing energy mix and other factors. As a result, the electricity mix looks very different across regions. At the same time, solar and wind are the most important energy sources in decarbonization scenarios for each region. A second new insight is that the question whether electricity production can rely 100% on renewable energy has lost relevance. Some research groups have argued for many years that electricity can be generated at 100% from renewable energy. Most research groups, however, included only small shares of renewable energy in decarbonization scenarios. Now, results have converged, with the most prominent research groups suggesting more than 90% renewable energy by 2050. Whether the full 100% can be reached has become more of an academic question as a result. These projections, however, show only a possibility. It will take a dedicated effort to continue the successful development of solar and wind energy seen in recent years.

The energy-economy models, including IAMs, draw on a very broad range of research results on energy sources. I take a closer look at three groups of research results. One group of research results concerns the key characteristics of different decarbonization options. Recent research has, for example, refined the understanding of the storage available for CCS, the sustainability of biofuels and the potential of hydropower. A second group of results concerns the cost of decarbonization options. This covers both the cost for individual energy sources and the cost of building a functioning system. A third group is the flexibility options that can be used to compensate the variability of solar and wind. Following the literature, they are classified into supply flexibility, grid extension, demand flexibility and energy storage.

This paper is a literature review, combined with the presentation of previously unpublished figures from scenario databases.[2] As such, the discussion of related literature is the main subject of the paper. However, there are somewhat similar publications, which compare modeling results from state-of-the-art energy-economy models. The results of the Energy Modeling Forum studies are often published in overview articles (Böhringer et al. 2021), which compare modeling results from several models. Similarly, the IAM community regularly publishes comparisons of modeling results (Hickmann et al. 2022; Guivarch et al. 2022; Luderer et al. 2022). However, these publications concentrate on very specific topics and not on broad global trends. A key related literature are papers which explicitly discuss how advances on integrating renewable energy into the electricity mix are reflected in energy-economy models (Pietzcker et al. 2017; Ueckerdt et al. 2017). This paper builds on these publications and derives policy-relevant conclusions and a less technical overview.

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[2] The databases collect data from peer-reviewed publications. While the publications focus on new but often very detailed aspects, this study is based on the data which provide an overview.

Section 2 presents an overview on how energy-economy models project optimal decarbonization of electricity production. Section 3 discusses the main ingredients in the studies: the different decarbonization options and their main features. Section 4 provides an overview of costs for the different options, both from an individual and a system perspective. Section 5 introduces the latest research on flexibility options to integrate solar and wind energy into the system. Section 6 concludes.

2. The electricity mix

There are many options to decarbonize the electricity system. Identifying which of them should be used to which extent requires model analysis. Energy-economy models determine the minimum cost at which the electricity system can operate under several constraints. These constraints include the natural limitations (or potential) for each energy source. Hydropower and geothermal energy, for example, are available only in limited amounts. Another constraint is the amount of land that can be used for biofuel[3] production, given the needs of food production and nature conservation. In this section, we present the results of several models, which are used for publications in top peer-reviewed journals as well as for the NGFS and the IPCC.

2.1 Historical trends

Before we come to the projections, let us consider recent developments. The share of solar and wind energy is growing exponentially, see the left panel of Figure 1. The share of electricity generation from coal, nuclear energy and oil is on a downward trend. In 2023, global annual renewable capacity additions increased by almost 50% (IEA 2024). Through a high share of hydropower, Ethiopia, Iceland, Nepal, and Paraguay already achieved a 100% renewable energy mix.[4] Germany, Greece, Ireland, the Netherlands, Spain, and Uruguay have achieved more than 37% of their electricity mix from solar and wind power in 2023, but are still surpassed by Denmark and Lithuania, which derive 67% and 57% of their electricity from solar and wind power, respectively. In the last-named eight countries, the share of solar and wind is increasing steeply. These countries thus demonstrate that high shares of solar and wind energy are feasible.

Just how relevant solar and wind energy have become in quantitative terms is illustrated in the right panel of Figure 1. The figure shows the yearly increase in total electricity generation in comparison to the yearly increase in solar and wind energy. Production increases in solar and wind energy has steadily approached the trendline for total electricity generation. If the trend continues, solar and wind energy production could soon exceed the total increase in electricity production. Once that happens, other energy sources will have to experience a net decrease in production. In 2022, 86% of electricity capacity additions have been renewable, a number which increases yearly (Mitri et al. 2023, p. 14).

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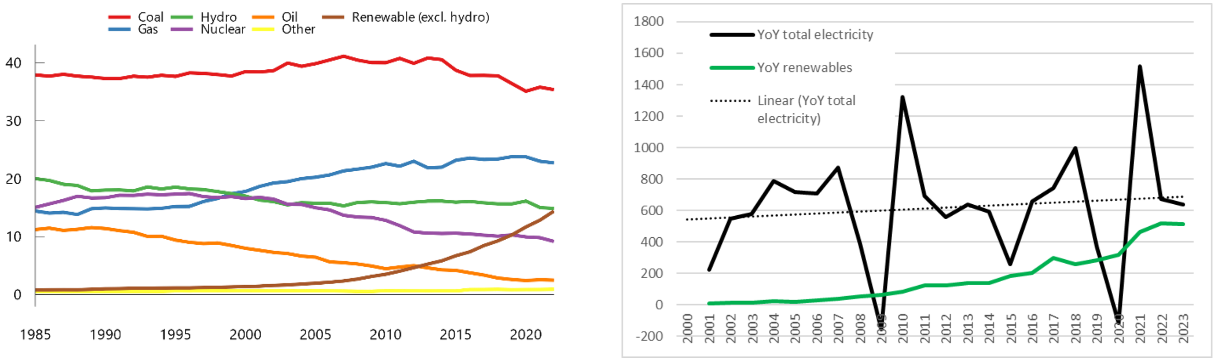
[3] Biofuels include crops and non-food plants. See Section 3.4 for a discussion.

[4] These countries vary strongly regarding the amount of electricity. Ethiopia, in particular, produces very little electricity. The point here is that reaching a high share of renewable energy in the global electricity mix will be aided by various renewable energy sources across the world. In Ethiopia, as in other countries in Sub-Sahara Africa, it is expected that renewable energy will have an important role in the further growth of electricity capacity (Cai et al, forthcoming).

Figure 1: Global trends in electricity production



Share of global electricity generation by fuel, 1985–2022 (percent)

Source: Energy Institute, Statistical Review of World Energy 2023.

Electricity production, from solar and wind energy and total, in TWh

Source: https://ember-climate.org/data-catalogue/yearly-electricity-data/

2.2 Model projections

Model projections for the global electricity mix vary widely, but also have some important commonalities. Figure 2 shows four examples. Data from the first three examples are downloaded from the scenario database of the NGFS Phase 4 Scenarios.[5] The NGFS uses three IAMs, see Table A1 in the appendix for further details. The Global Change Assessment Model (GCAM) 6.0 is developed by the Joint Global Change Research Institute in the United States. MESSAGEix-GLOBIOM 1.1-M-R12 is developed by the International Institute for Applied Systems Analysis (IIASA) in Austria. REMIND-MAgPIE 3.2-4.6 is developed by the Potsdam Institute for Climate Impact Research in Germany. The charts of these three models in Figure 2 are from the "below 2°C" scenario. The bottom right chart shows a projection of the "World Energy Model" developed by the International Energy Agency (IEA 2021a). The model is described as "a large-scale simulation model designed to replicate how energy markets function". The scenario shown is for "Net Zero Emissions" (NZE).

The energy-economy models discussed in this paper identify the lowest cost electricity mix that stays within the carbon budget defined by the chosen scenario. They do not model policy instruments explicitly, but an emission trading system with certificates equal to the carbon budget (or an equivalent carbon tax) would achieve the modeled electricity mix. Technological progress is calibrated on historical learning rates, which relate the increase in capacity produced to the reduction in cost.

The results show that models make use of all decarbonization options available today. Solar and wind energy expand strongly, though to different degrees, in all models. Hydropower and geothermal energy are used as well, while it is also clear that their potential is limited. The role of nuclear energy varies from a slow phase-out (GCAM), to maintaining today's capacity (REMIND) and a doubling of today's capacity (WEM, MESSAGEix). MESSAGEix also shows the use of carbon capture and storage (CCS), used on natural gas power plants. All models use some amount of biomass. When bioenergy is combined with CCS, abbreviated as BECCS, negative emissions can be achieved: In a first step, plants absorb CO2 from the atmosphere through photosynthesis and are then harvested and processed into bioenergy. In a second step, the bioenergy is burnt, and the energy is used, but the resulting CO2 is captured and stored underground. This option is used mostly

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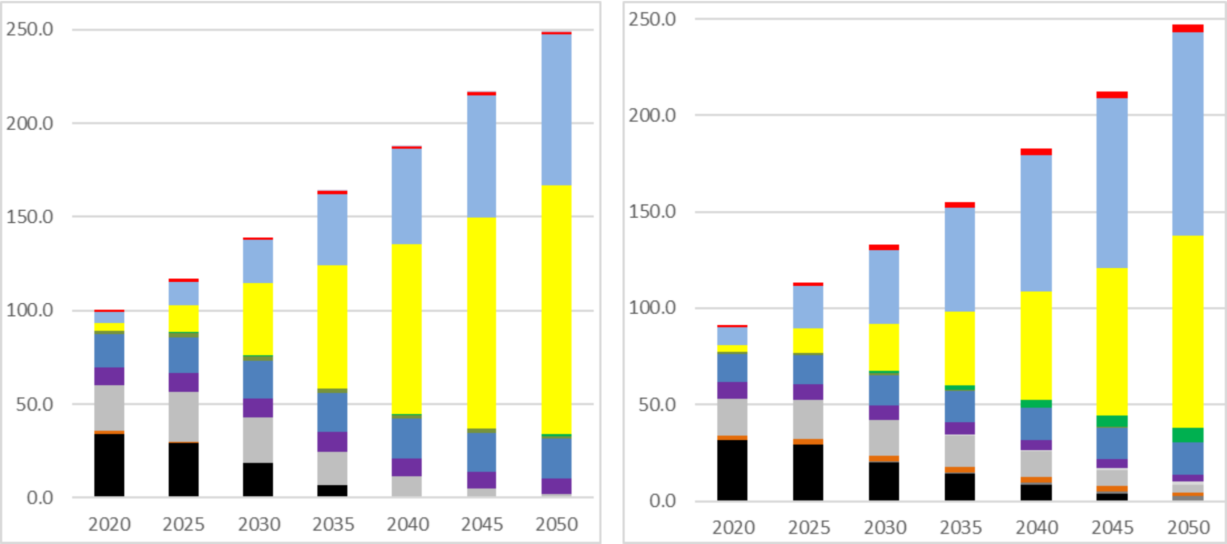
[5] Documentation for the NGFS Phase 4 Scenarios Explorer is available here: https://data.ece.iiasa.ac.at/ngfs/#/docs

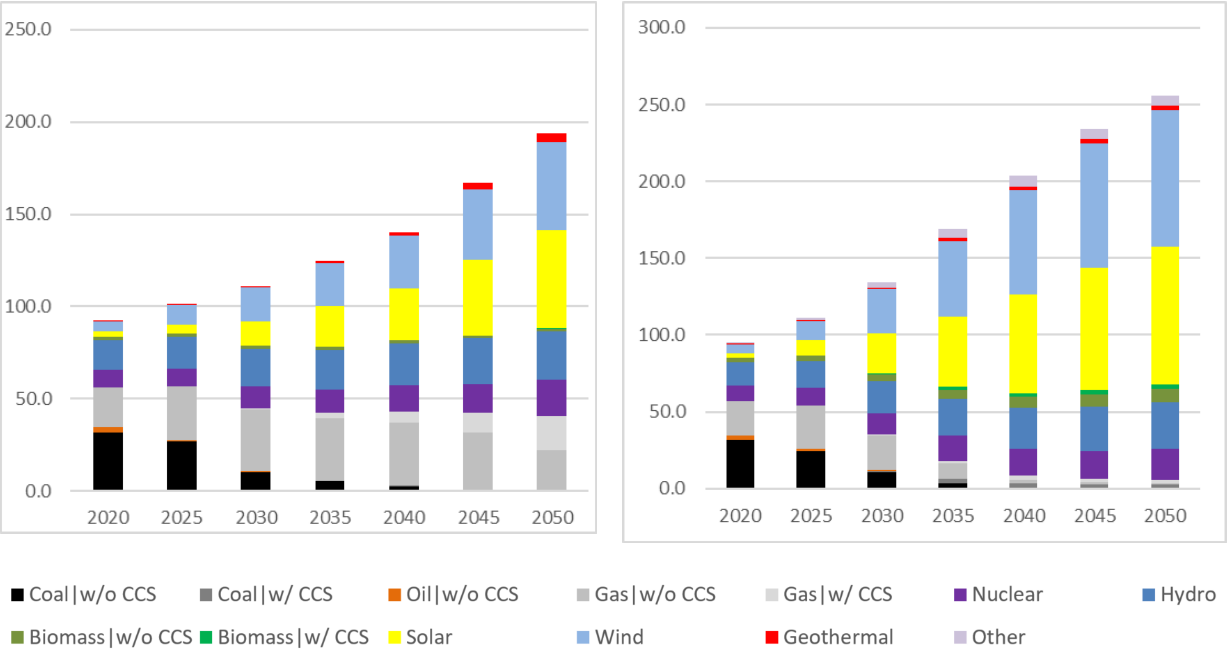
by GCAM and WEM. Section 3 provides a more detailed discussion of the potential and limitations for each option.

Figure 2: Global electricity mix (EJ/year) in 2023 NGFS scenario and from IEA

REMIND-MAgPIE 3.2-4.6 **GCAM 6.0 NGFS**



MESSAGEix-GLOBIOM 1.1-M-R12 **WEM 2021**



Source: Panel 1 to 3: NGFS (2023), Panel 4: IEA (2021a)

In addition to the decarbonization of the electricity sources, it is important to note the amount of electricity use projected by the three models. In MESSAGEix, electricity production increases by a factor of 2.1 between 2020 and 2050. In WEM, Remind, and GCAM it grows by factors of 2.5, 2.5 and 2.7, respectively. According to Section 2.3 of the NGFS technical documentation, scenarios have “harmonized population and economic developments”, which are “based on projections from the IMF” (NGFS 2023a). The differences in total electricity production thus do not originate in different economic development trajectories. According to the documentation (NGFS 2023a, Section 1.1), policy assumptions are also fixed for a given scenario.

There are thus three determinants explaining the differences in total electricity production. One is energy efficiency. This depends on the economic value added derived from a unit of electricity, a variable which has historically trended up steadily. A second determinant of electricity production is electrification. In sectors like transportation and buildings, substituting the direct use of fossil fuels with electricity is an efficient way to decarbonize. The degree of electrification thus determines the demand for electricity. Finally, cost projections determine the supply price of electricity. The learning rate for solar energy has been very stable for a long time (Creutzig et al. 2017). If the resulting cost decreases continue, the supply cost of electricity will be low. The low supply cost translates into higher demand, so that production will be high.

2.3 Regional variation

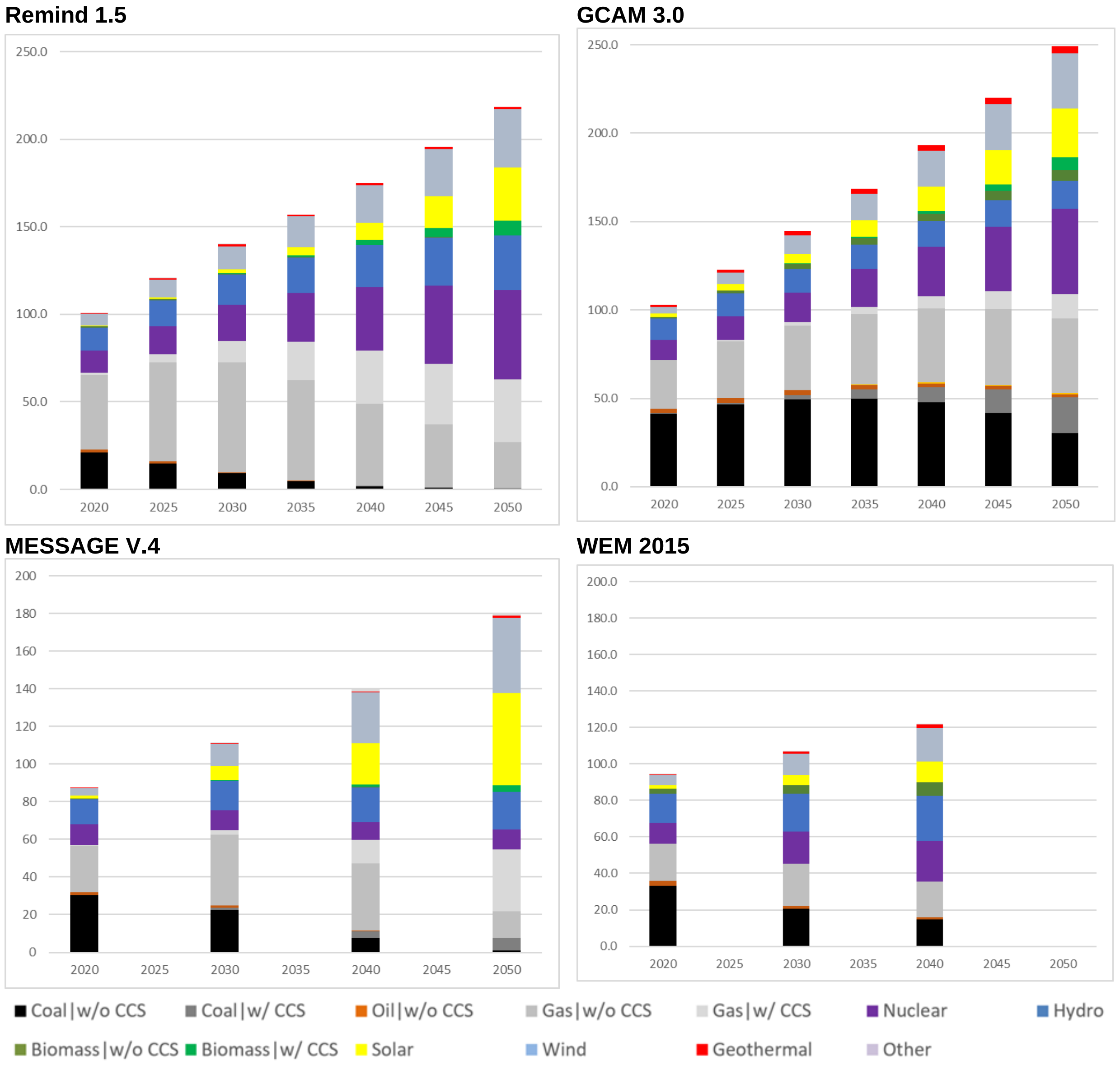
In the previous subsection, we have seen that at the global level, models identify solar and wind energy as the optimal energy source for most of the electricity supply. However, the conditions for electricity production vary by region. The efficiency for using solar energy, for example, is obviously better in regions close to the equator and with less cloud cover. Could it be that for some world regions, the widespread adoption of solar and wind is not the right strategy to decarbonize the electricity system? The models used for Figure 2 are global models, but they divide the world economy into 11 to 32 world regions. To illustrate regional variation, regional energy mixes for one of these models, REMIND, are shown in Figure A1 in the appendix. The figure shows that the energy mix does vary by region, meaning that the models take local energy production conditions into account. It also shows that region-specific differences in demand growth are modeled explicitly. Nevertheless, solar and wind energy emerge as the most important energy source in all regions.

2.4 Development over time

As technology develops, projections of the optimal electricity mix evolve. Both the declining cost for renewables and improved flexibility options (Pietzcker et al. 2017) caused gradually increasing shares of renewable energy in integrated assessment modeling results. Figure 3 shows how the electricity system was projected to look like in a publication from 2015. The figure shows a “below 2°C” scenario, which was described by the concentration of greenhouse gases in the atmosphere as “450 ppm CO2e” at the time. The results are shown for earlier versions of the models used in Figure 2 (data from the IEA model does not seem to be available from the time). Considering these previous projections is important to understand why natural gas, CCS and nuclear energy used to be considered key technologies for the decarbonization of electricity production.

There are three important differences between the earlier and newer results. First, natural gas and coal play a much bigger role in previous results. This reflects the concept of “baseload” that was prevalent at the time. A “baseload” of fossil fuels was intended to be used to balance the variability of solar and wind energy. It has been replaced with the concept of “flexibility options”, which is explored in Section 5. Second, the earlier results make much more use of CCS. CCS is combined with coal, natural gas, and biomass. The potential and limitations of CCS are explored in Section 3.3. CCS is still given a role in newer model results, but solar and wind have become the more attractive option due to the cost declines. A third difference is that the earlier results rely much more heavily on nuclear energy. Since then, nuclear energy has lost ground in terms of relative prices, see Section 3.5 and Figure 7.

Figure 3: Global electricity mix (EJ/year) in 2014 IPCC scenario



Remind 1.5

GCAM 3.0

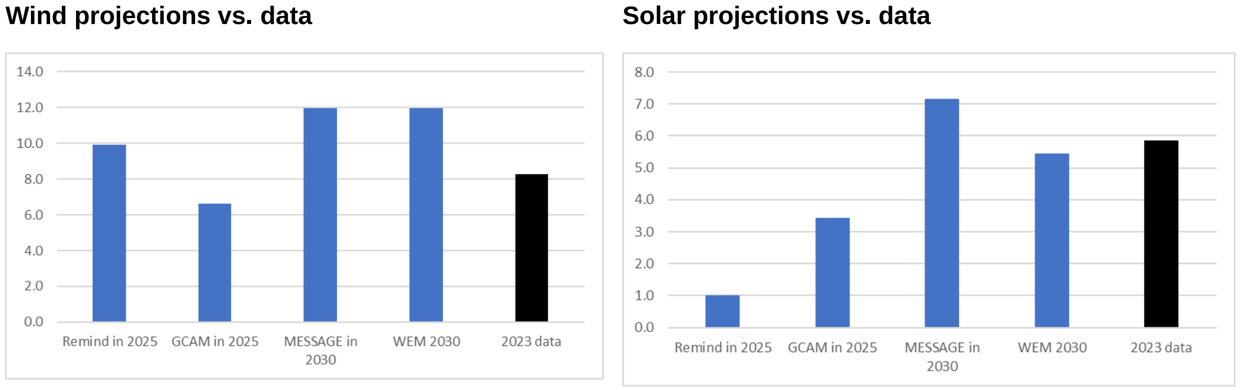
MESSAGE V.4

WEM 2015

Source: Panel 1 to 3: AR5 Scenario Database, Riahi et al. (2015), Panel 4: IEA (2015)
Note: The scenario shown in the first three panels is “AMPERE2-450-FullTech-OPT”. It is described as “Global emissions follow an optimal pathway assuming immediate introduction of climate policies to meet the long-term targets (450 ppm CO2e).” For further details, see the source. The results of the AMPERE project were included in the IPCC AR5 report of 2014. Panel 4 shows the “450 ppm” sceario of the 2015 WEO, publised by the IEA.

We can verify that the change in modeling projections reflects more than just a new fashion among modelers. Figure 4 compares the climate scenarios of Figure 3 with the actual electricity production of solar and wind energy. Wind energy production in 2023 has already exceeded the projection for 2025 in the GCAM model and is not far off from the projections for 2025 and even for 2030 in the other three models. Solar energy production in 2023 has exceeded both projections for 2025 and one of the projections for 2030, while being close to the other for 2030. This shows that modelers had underestimated the potential for solar and wind energy in 2014/15.

Figure 4: Comparison of energy production with solar and wind (EJ/year)



Sources: Riahi et al. (2015), IEA (2015), https://ember-climate.org/data-catalogue/yearly-electricity-data/

Note: All projections were published in 2015 (see sources). The first two bars show projections for 2025. The third and fourth bar show projections for 2030. The fifth bar show the actual energy production in 2023.

2.5 100% renewable electricity?

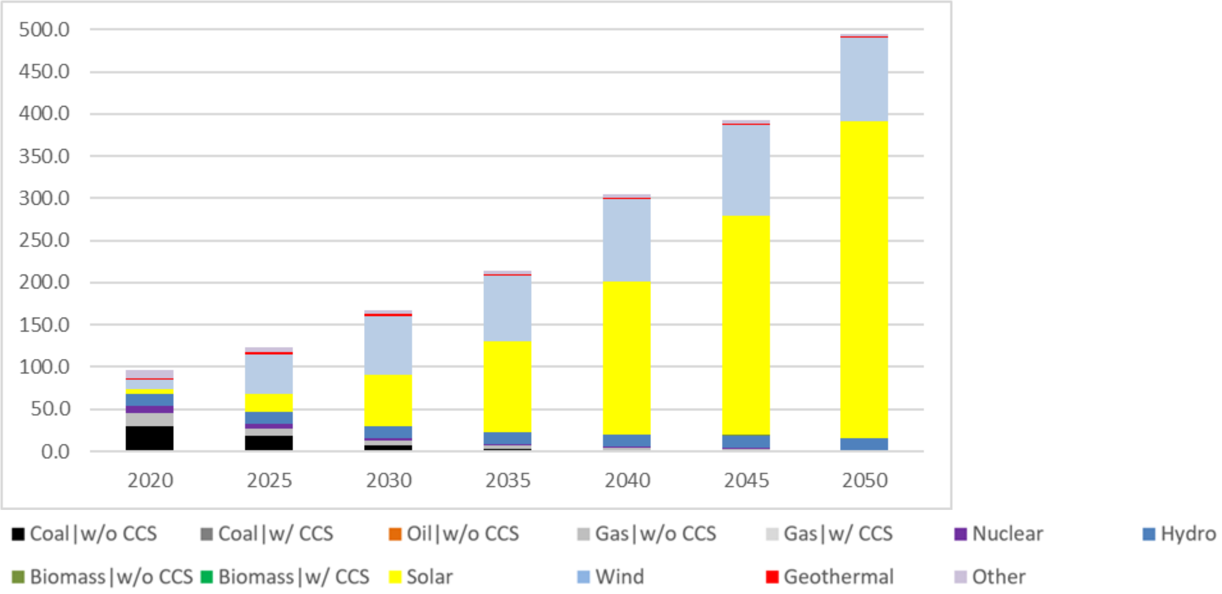
By 2050, the four models in Figure 2 project achieving high shares of renewable energy in the generation of electricity: GCAM has a share of 94.6%, MESSAGE 69.0%, REMIND 95.8% and WEM 90.0%. The models thus have a high level of confidence in the use of flexibility options, which are used to compensate the variability of solar and wind energy. Further, the results show that ambitious climate targets can be reached without achieving 100% renewable energy by 2050, through the use of CCS and nuclear energy. Finally, several countries with good conditions for hydropower have already achieved 100% renewable energy in their electricity mix. Despite this reassuring information, some researchers are interested in the question whether *globally*, 100% of electricity can be generated with renewable energy at reasonable cost.

Figure 5 shows model results from the LUT-ESTM model that projects a share of 99.9% renewable energy in the electricity mix by 2050 (Bogdanov et al. 2021). By 2050, only marginal amounts of nuclear energy and natural gas are still in use. The model is described as an energy system transition model and is engineering-based. In addition to the large share of renewable energy, the model reflects that large parts of the energy system (like transportation, heating, and industrial production) are electrified: The model projects that electricity production grows by a factor of 5.1 between 2020 and 2050, which is much larger than in the models shown in Figure 2.

There is a large number of peer-reviewed publications on 100% renewable energy (Hansen, Breyer, and Lund 2019), including in top journals (Bogdanov et al. 2019; Haegel et al. 2019). However, 100% renewable energy studies are also criticized for using overly optimistic assumptions, for example on cost for renewable energy and flexibility options. What matters in the end is the widely agreed result that renewable energy can supply *almost* the entire energy needed for electricity production. In a way, the important difference is between the mixes described in Figure 2 and Figure 3 and less the difference between Figure 2 and Figure 5.

LUT-ESTM is an hourly resolved electric power system model. Research based on such models provides a valuable complement to IAMs. Victoria et al. (2020) confirm that solar and wind energy can become the main pillar of electricity production in a fully decarbonized energy system and that installation rates need to be similar to historical maxima. Sepulveda et al. (2018), however, point out that the “firm” low-carbon resources nuclear, reservoir hydro, geothermal, bioenergy, and fossil plants with CCS allow reducing cost by as much as 62%, by providing electricity in those moments where solar and wind energy production is low.[6] Three years later the same modeling team offered an additional perspective: Long-duration energy storage (LDES) could entirely replace the need for firm low-carbon resources, if energy storage capacity costs fall sufficiently (Sepulveda et al. 2021). LDES includes a range of technologies grouped into electrochemical, chemical, thermal, and mechanical options. This research thus contributes the insight that the economic viability of 100% renewable energy systems hinges crucially on the technological progress in LDES.

Figure 5: Model results for LUT-ESTM 2.0



Source: (Bogdanov et al. 2021)

Transitioning to an electricity system with a very high share of renewable energy might seem like a questionable objective from a portfolio management perspective. Having a diversified portfolio of options, each with different risk profiles, is generally desirable. However, the models make use of the flexibility options described in Section 5 and these options are effectively additional options in the portfolio of electricity grid operators: Energy storage provides a backup, demand flexibility helps matching demand and supply, and grid extensions create additional options by providing access to geographically remote electric generators. Generally, the models take into account the probability distribution of wind and solar availability and design the electricity system in such a way that even during “dark doldrums”— periods with low wind and solar generation—electricity supply is stable.

3. Types of low-carbon electricity production

COP 28 ended with an agreement to “transition away from fossil fuels”. This reflects that the use of all unabated fossil fuels must stop completely if climate change is to be stabilized at any level. That is, even for the temperature to stabilize at more than 2°C, fossil fuel use needs to end. In this section, we give an overview of six different options for decarbonizing electricity production. When looking at the advantages and disadvantages of each option, three important determinants emerge. First, cost is a key determinant of course, which is analyzed in detail in Section 4. A second determinant is variability, which is the subject of Section 5. A

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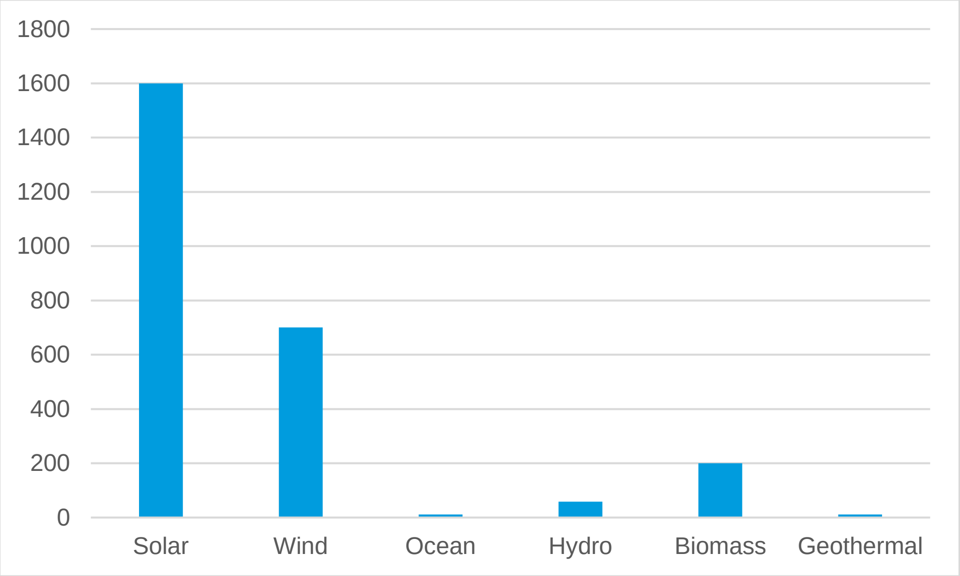
[6] The paper used the term “firm” for energy sources that are not variable.

third determinant is the technical potential, for which Figure 6 gives an overview. The figure shows that solar and wind energy have a much larger potential than all other types of renewable energy.

Figure 6: Potential of renewable energy sources, in EJ



Source: Solar to biomass: Tomabechi (2010), Geothermal: Klimenko, Tereshin, and Mikushina (2009)
Note: Moriarty and Honnery (2012) provide an overview of estimates for the potential. The references are chosen for being close to estimates from many other studies. EJ = exajoule = 10^{18} J.

3.1 Solar and wind energy

There are two key factors that explain why solar and wind energy are the main sources for capacity additions in Figure 2: the technical potential and the low cost. Unlike hydropower and geothermal power, solar and wind energy are available around the world. The availability differs, but every country has substantial potential in at least one of these renewable energy sources. Bogdanov et al. (2019) provide a map of which renewable energy source each region of the world can rely on as their main source of energy (while all regions rely on a mix). A few regions, like Brazil, Canada and Norway have so much potential for hydropower that their electricity systems can rely on that. Other areas, like southern Argentina, the northern United States and the British Isles can rely mainly on wind energy. Most countries, however, especially those around the equator, can source their electricity from solar energy. A few remaining regions would do best with a mix of renewable sources, where several types have similar shares. The cost advantage of solar and wind energy is discussed in Section 4.1.

The two main challenges for solar and wind are the variability of supply as well as the reliance on transition metals. The variability of supply of these two energy sources can be addressed by making the electricity system more flexible. How this can be achieved is discussed in Section 5. Another concern is that the exponential growth in solar and wind energy requires a rapid increase in the “transition metals” required for these technologies. Transition metals are projected to reach their historical maximum during the energy transition (Boer, Pescatori, and Stuermer 2024). There are, however, three economic effects that can be expected to soften the impact of the energy transition on commodity markets. First, surging demand provides a price signal to increase supply. Second, the various transition metals are partial substitutes for each other, so that extreme shortages in one type can be bypassed. And third, rapid technological progress might reduce the need for transition metals. For a detailed discussion on the role of transition metals, see Kim, Panton, and Schwerhoff (2024, p. 21-23).

Another challenge is that solar and wind energy require land. In many cases, there is local opposition to the construction of solar and wind projects. The exponential growth of solar and wind power shown in Figure 1 highlights that, so far, pragmatic solutions have been found. Further, other electricity generation technologies, like hydropower and coal power, use more land than solar and wind.[7]

3.2 Hydropower and geothermal energy

Hydropower and geothermal energy have similar properties that determine their role in the electricity system. A key advantage is their relatively low cost. Neither of these technologies is shown in Figure 7, because the cost per MWh depends strongly on the location and the size of the power plant. However, IRENA lists both energy sources at prices below the cost range for fossil fuels (IRENA 2023). Both sources are a bit more expensive than solar and wind power in terms of levelized cost of electricity (LCOE). However, geothermal energy is extremely reliable, and hydropower is still very reliable except for extended droughts. Flexibility options as described in Section 5 for solar and wind are thus not needed. To the contrary, they can even be used to compensate the variability of solar and wind (Ricks et al. 2024). This makes these sources very attractive financially. The reliable supply of electricity is the second important advantage of these two sources.

An important disadvantage of hydropower and geothermal power is that they have limited potential, see Figure 6. Geothermal energy is available only in certain geographical areas and cannot always be exploited safely (Jolie et al. 2021). Similarly, hydropower depends on availability. A recent study found that Europe has nearly exhausted its hydropower potential, while more potential is available in the Himalaya and Africa (Xu et al. 2023). The study has taken into account that much of the technical potential cannot be used, because flooding large areas for hydropower dams can be environmentally harmful and/or would require displacing the local human population. Models projecting the electricity mix thus typically expect that more of the unused potential is exploited and currently operating capacity is maintained. However, the large increase in electricity demand cannot be sourced from these two sources.

3.3 Carbon capture and storage

Carbon capture and storage (CCS) is defined as a process in which carbon dioxide from industrial sources is separated, treated, and transported to a long-term storage location. It is relevant for electricity production, because it can be combined with power plants using fossil fuels to prevent the release of the CO2 into the atmosphere. Figure 2 shows the use of CCS in projections. The GCAM and Message models have visible amounts of CCS, in combination with natural gas and biomass. An important advantage of CCS is that it can be combined with existing fossil fuel power plants and largely neutralize their emissions. Further, the combination of bioenergy and CCS (BECCS), allows withdrawing emissions from the atmosphere. In the production of bioenergy, CO2 is naturally absorbed from the atmosphere by plants. When the CO2 is captured and stored while the bioenergy is burned, the CO2 is not released back into the atmosphere.

The key limitation for CCS is that the amount of CO2 that can be stored safely every year is limited. Fuss et al. (2018) discuss the various CCS techniques and show that up to 5 Gt of CO2 per year can be absorbed through BECCS and up to 3.6 Gt through afforestation, for example. All technologies together can absorb as much at 10 Gt per year (Fuhrman et al. 2023). However, current global emissions are at about 50 Gt per year. This means that CCS can only be used for residual emissions, meaning those that are very expensive to abate. Therefore, fossil fuels cannot be used at a large scale, because their unabated emissions would exceed carbon budgets. Electricity production, therefore, must switch almost completely to energy sources other than fossil fuels. A related concept is the use of captured CO2 (which is why the concept of CCS is sometimes extended

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[7] https://ourworldindata.org/land-use-per-energy-source

to carbon capture, *utilization*, and storage, CCUS). This, however, is limited to only an additional 0.5 Gt per year (Hepburn et al. 2019).

3.4 Biofuels

Biofuels, also called biomass or bioenergy, comes in different types. Traditional biomass, mostly fuel wood and charcoal, is still used as an energy source in developing economies, but not for electricity generation. Biofuels for electricity generation are distinguished in first generation, where a crop is used directly, and second generation, which are produced from non-food plants (Banerjee 2023). An important advantage of biofuels is that the fuel, which is very similar to petroleum products, is very flexible and convenient to use. A second important advantage is that, in combination with CCS, it can be used to extract CO2 from the atmosphere (Hanssen, Daioglou, Steinmann, Doelman, et al. 2020).

An important limitation of biofuels is that they require a large amount of land to be produced. This means, biofuels production, especially the first-generation type, competes with food production and nature conservation. When land use becomes more efficient, it would be possible to responsibly reconcile biofuels production, food production and land conversation. However, the potential is still limited (Daioglou et al. 2019). Second-generation biofuels are less cost-efficient, but still have a considerable potential (Hanssen, Daioglou, Steinmann, Frank, et al. 2020).This is reflected in a limited use of biomass in the modeling results shown in Figure 2. Other concerns regarding sustainability include the water footprint (Jeswani, Chilvers, and Azapagic 2020).

3.5 Nuclear energy

The advantage of nuclear energy is that it reliably provides low-carbon electricity. Nuclear power provides stable and continuous electricity generation, which can complement intermittent renewable energy sources like wind and solar. This stability “can help ensure secure, diverse low emissions electricity systems” (IEA 2022a). In scenarios where deep decarbonization is necessary, the IEA sees nuclear energy as playing a significant role in the energy mix alongside increased deployment of renewable energy technologies, see Figure 2, panel 4.

However, nuclear energy has two important limitations from an economic perspective.[8] One limitation is that nuclear fuel, uranium-235, is not available in sufficient quantities for a substantial expansion of nuclear energy (Muellner et al. 2021). This means that nuclear energy will not be able to avoid more than the 2 to 3% of total global GHG emissions it avoids currently. The possible shortage of nuclear fuel has been pointed out repeatedly (Gabriel et al. 2013; Monnet, Gabriel, and Percebois 2017; Böse et al. 2024). However, advances in exploration and mining technologies may extend these reserves further, while improvements in the fuel efficiency of nuclear reactors, the advances of technologies for recycling and reprocessing nuclear fuel, and the emergence of new technologies such as Small Modular Reactors and Generation IV reactors which improve fuel efficiency, reduce waste, and expand the range of fuel sources beyond conventional uranium could help ensure that nuclear energy can continue to contribute effectively to global decarbonization goals.

Another limitation is the high cost. Figure 7, based on the data by Way et al. (2022) shows that nuclear energy cost keeps increasing and that it is now the most expensive of the major energy sources. This pattern of cost is confirmed in several peer-reviewed studies. Lovering, Yip, and Nordhaus (2016) find widespread cost escalation, which is mild in many countries and “rapid” in the United States, with exceptions only for some countries and specific eras. Five years later, Wealer et al. (2021) find that cost escalations still continue. The

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[8] Given the focus of this paper on the economics of electricity supply, operational safety and nuclear waste disposal are not discussed.

research concludes that “investing in nuclear power plants is not profitable”, even when reactor lifetimes are extended. In addition, the cost of insurance for nuclear energy is so high that it is not possible to obtain insurance from the private insurance market. Instead, the government provides insurance, which amounts to a very substantial subsidy (Laureto and Pearce 2016).

The nuclear industry tried to counter the cost increase by developing small modular reactors (SMRs). The idea is to standardize production and achieve scale effects. Compared to conventional nuclear power plants, SMRs have lower initial investment cost, shorter construction times, and the capability to operate in small and medium-sized power grids (which reduces the need for long-distance power transmission). The IEA supports continued research and development in advanced nuclear technologies, such as Small Modular Reactors, to improve safety, efficiency, and cost-effectiveness (IEA 2022a). However, this too is not without challenges. The International Atomic Energy Agency (IAEA) finds “several technical, economic, regulatory and supply chain challenges” (Vaya Soler et al. 2021). Further, the actual cost exceeds the anticipated cost by a very large margin, so that first efforts to build SMRs have been replaced with plans to build solar and wind capacity (Cho 2023). Studying the potential for SMRs in developing countries, L’Her et al. (2024) find that 95% of the potential market is eliminated due to governance concerns, or because SMRs couldn’t be operated economically. Finally, the nuclear waste from SMRs is more difficult to handle and dispose of than for conventional nuclear reactors (Krall, Macfarlane, and Ewing 2022).

The production of nuclear energy has been stable for a long time and is expected to remain so. Electricity production with nuclear energy has increased in China from 111 TWh in 2013 to 433 TWh in 2023, according to data from https://en.china-nea.cn/. In the United States, Russia, and India, however, production did not change much. At the global level, electricity production with nuclear energy in 2023 was at 2678 TWh, close to the 2601 TWh in 2003. For the decade 2011 to 2020, the IEA recorded a net decrease of nuclear energy capacity by 5 GW. For the decade 2021 to 2030, the IEA projects that 11 GW will be retired, while 18 GW will be added (IEA 2022b). The surplus of 7GW will thus compensate the loss of the previous decade. Depending on the evolution of its cost, however, nuclear energy could play a more important role. A report by MIT Energy Initiative concludes that if the cost of nuclear energy declines, “least-cost portfolios include an important share for nuclear” (MITei 2018). The IEA estimates that in order for nuclear to “fulfil its role” cost would have to decrease from the current value of USD 9 000/kW to USD 5 000/kW and for nuclear to have a “larger role”, cost would have to decline to USD 2 000-3 000/kW (IEA 2022a, p. 9).

3.6 Nuclear fusion

Nuclear fusion is considered an attractive option for future electricity generation, but is not expected to be available in time for net zero emission targets at mid-century (Nicholas et al. 2021).

4. The role of cost

The levelized cost of electricity (LCOE) is an important measure of cost for electricity. It is defined as “the price at which the generated electricity should be sold for the system to break even at the end of its lifetime” and is equivalent to the net present value lifetime cost divided by discounted total electricity produced. It is relatively straightforward to measure, and it allows a direct comparison of the different sources. In a first step, we will thus discuss LCOE for different technologies. However, the cost for producing electricity does not fully reflect that different types of electricity vary in complementary investments needed, like the electricity grid, energy storage and demand flexibility. Solar and wind energy, for example, are variable, so that the system needs the capacity to compensate through complementary investments when they don’t produce electricity. Nuclear energy can produce steady electricity, but it takes a while to ramp up production, so that it is not ideal to compensate variable energy source. Natural gas and hydropower, by contrast, have very high availability and can compensate variable sources. When the electricity system has a high share of variable sources, electricity from natural gas and hydropower is more valuable than electricity from nuclear, which in turn is more valuable than solar and wind energy. This value to the system needs to be traded off with LCOE. The system perspective is thus discussed in the second step.

4.1 Relative cost of energy sources

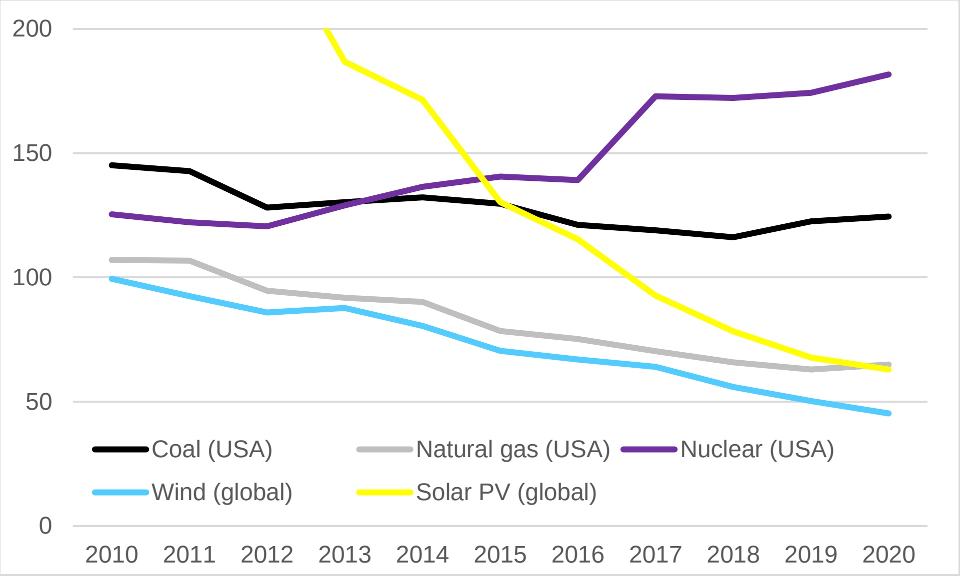
Way et al. (2022) provide a very comprehensive analysis on LCOE, which is built on many data sources. Figure 7 shows an excerpt of the data for the years 2010 to 2020. They find that in 2020, the lowest-cost technology for generating electricity was wind energy, followed by solar energy. Both technologies have experienced steady cost declines. Next is electricity generated by natural gas and coal. Electricity generation cost with these technologies have fluctuated without a clear trend in the long term. The shale gas boom caused a significant cost decline in the United States in the 2010s, though (Mayfield et al. 2019). The most expensive of the major technologies for generating electricity is nuclear energy, which has been on an upward cost trend since the first reactors were constructed. Confirming the results of (Way et al. 2022), the International Renewable Energy Agency also finds that solar and wind energy have lower LCOE than all types of fossil fuels (IRENA 2023). These relative prices have changed dramatically over 20 years. In the year 2000, natural gas and coal were by far the lowest cost technologies, followed by nuclear and then solar and wind energy.

While solar and wind energy are thus the lowest-cost options in terms of LCOE, they are also intermittent, meaning that their supply depends on weather and daylight. Section 5 will discuss how intermittency can be addressed. Here we take a look at the cost of energy storage technology. Way et al. (2022), for example, show the cost trends for two energy storage technologies. One of these technologies is batteries, which can be used at industrial scale to save energy from times with abundant solar and wind energy for times with a shortcoming. A second energy storage technology is called “power-to-X”. This refers to the technology for converting electricity generated by solar and wind energy to a fuel. The “X” represents that this could either be a gas, like green hydrogen, or a liquid, like ammonia. The idea of this technology is to convert excess solar and wind energy to a fuel that can later be converted back to electricity. According to Way et al. (2022), battery cost declined by 68% between 2010 and 2020 and the cost for power-to-X declined by 71% in the same timeframe. It reflects that both technologies are used increasingly, following demand.

Figure 7 provides a useful overview of the state of technology development. At the same time, the effective cost in each country depends on several local determinants. A key determinant is the interest rate. Renewable energy has a higher upfront investment cost (capital expenditure) and lower ongoing cost (operating expense). A recent assessment finds that the share of capital in total cost is only 15% for fossil fuels and as high as 91% for onshore wind (Beiter et al. 2024). This means that changes in interest rates could affect renewable energy more than fossil fuels. In EMDEs, borrowing cost can “more than double the cost of renewable electricity production” (IMF 2023). In countries with very high financing cost, the effective cost might thus be higher than indicated by Figure 7. However, developing countries willing to construct renewable energy capacity have the option to seek support from the multilateral banks or other forms of international support (IRENA and CPI 2023).

The models used for Figure 2 take technical and economic considerations into account. Investments into electricity capacity is, however, also influenced by political considerations. Efforts to create or maintain local jobs and local vested interests can influence investment decisions in favor of coal (Montrone, Ohlendorf, and Chandra 2021; Ayas and Wiseman 2022; Hanto et al. 2022). Corruption can also prevent a transition to renewable energy (Amoah et al. 2022). It is thus important not to take investment decisions as evidence for relative cost. Political considerations can cause an investment choice in favor of energy sources that are not least-cost.

Figure 7: Cost of electricity generation in LCOE by source (2020$/MWh)



Source: Way et al. (2022). The years 2010 to 2012 for solar PV are cut off. The values are: 2010: 422.8 $/MWh, 2011: 321.4 $/MWh, 2012: 241.6 $/MWh.

4.2 The cost of energy systems

Solar and wind energy have the lowest LCOE compared to other main energy sources. This does not mean that only these sources can be used to power an electricity system. To determine the least cost design of an entire energy system requires a model which captures the most important cost determinants in reasonable detail. One of these determinants is location-specific cost of energy sources (Figure 7 shows only global averages) and the profile of electricity production, at daily, weekly, and seasonal scales. A second determinant is the initial electricity mix. For example, countries or regions with lower shares of solar and wind energy can more easily integrate additional capacity from these sources than regions that have already a high share. A third determinant is the existing infrastructure for flexibility options. Countries with a strong electricity grid or readily available hydropower can integrate solar and wind energy more easily.

The models shown in Figure 2 minimize the system cost of electricity production, while considering several constraints. One of the constraints is the necessity to satisfy electricity demand at any point in time, including those times when solar and wind energy is not available. This is achieved, for example, by using probability distributions for the availability of solar and wind energy. Additional constraints can be added in scenario design. A key constraint is the total amount of emissions generated by the modeled electricity mix. The models shown in Figure 2 all restrict total emissions to an emission budget that keeps the global temperature increase at below 2°C. Despite having the options of CCS, bioenergy, and nuclear energy at their disposal, the models find a dominant share of solar and wind energy optimal.

The models in Figure 2 thus inform us that an electricity system based on solar and wind energy is the lowest cost option to stay below 2°C. This switch to solar and wind is even faster when the temperature target is lower, for example at 1.5°C. However, another policy-relevant question is how the cost for an electricity system based on solar and wind compare to the cost of an electricity system that is based on fossil fuels. Solar and wind have lower LCOE but also require flexibility options. What is the quantitative trade-off between this advantage and limitation? Only some research articles formulate clear answers. Way et al. (2022), or example, find that “compared to continuing with a fossil fuel-based system, a rapid green energy transition is likely to result in trillions of net savings”. Bogdanov et al. (2019) find “100% renewable electricity systems highly cost competitive”. In a study on India, Lu et al. (2020) find “renewables could provide a source of power cheaper or at least competitive with what could be supplied using fossil-based alternatives.”

5. Flexibility options

How can we reconcile the very quick transition to solar and wind energy documented in Section 2 with the intermittent nature of these two energy sources? Electricity systems can be balanced, despite a high share of intermittent energy sources, by various types of flexibility options (Cruz et al. 2018). Following Pietzcker et al. (2017), this section is divided into the four main types of flexibility options: supply elasticity, grid extension, demand flexibility and energy storage. Cost can be minimized by employing an optimal combination of these four options. Given that countries have only recently pioneered higher shares of intermittent electricity sources, they have come into use only to a limited extent. But this is changing already. The US, for example, is experiencing a boom in battery storage capacity, which is expected to continue (eia 2024).

The most widely used of the four types of flexibility options is supply elasticity. Adjusting electricity supply from other sources is almost automatic as soon as solar and wind energy enter the electricity grid. Currently, those countries with quickly increasing shares of renewable energy are also investing more into grid extension and electricity storage. In the United States, Europe and “OECD Pacific”, there is a long-term upward trend in grid investments and grids are becoming increasingly digital (IEA 2023a). For energy storage the growth rates are much higher. The IEA projects grid battery storage to increase by more than a factor six between 2020 and 2026, while pumped hydro storage also increases substantially, mostly in China (IEA 2021b). The least advanced of the four options is demand flexibility but countries started using it already and are adjusting their legal framework for it (IEA 2023b). All four options are thus increasingly phased in, as the share of intermittent energy increases.

5.1 Supply flexibility

Power plants from non-intermittent sources can be used to offset the variability and supply electricity whenever intermittent sources are not producing enough. Existing natural gas capacity, for example, can be used as a complement to intermittent sources (Baranes, Jacqmin, and Poudou 2017). Figure 2 shows that natural gas is expected to be part of the energy mix for many years, while coal is phased out much faster. Adding capacity in natural gas, by contrast, risks oversupply (Gürsan and de Gooyert 2021). Further, it might turn into stranded assets when electricity production needs to decarbonize entirely (Kemfert et al. 2022).

Many countries currently use substantial amounts of hydropower. In Latin America, for example, all countries have a share of hydropower of at least 10%. Hydropower can take on the role of stepping up electricity production when supply from intermittent sources is low (Dimanchev, Hodge, and Parsons 2021). This is particularly important when high shares of solar and wind energy are reached in electricity generation and the use of natural gas and coal is no longer desired.

5.2 Grid extension

The second type of flexibility option is to pool intermittent energy supply from a large geographical area. This requires creating a well-connected electricity grid (Tröndle et al. 2020). The availability of electricity from solar and wind energy varies between the two technologies and by geographic region. Steady supply can thus be achieved by connecting intermittent sources from a large geographic area. Regions that are not connected would have much higher cost than interconnected regions and less efficiency (Child et al. 2019). Transcontinental power pools enable renewable energy to meet 100% of electricity demand (H. Yang, Deshmukh, and Suh 2023).

Countries expand their domestic electricity grid, but international electricity trade is an important option as well. Electricity trade is not practical for island economies like Australia and Japan. The US, China, and other very large economies can achieve a lot of flexibility by extending the domestic grid. China, for example encourages cooperation in investment, equipment, technology, standards, and training between provinces. For all other countries, better international electricity connections and more electricity trade facilitate the integration of intermittent energy sources. International electricity trade also functions as mutual insurance against strong price volatility or electricity supply deficit. Bidirectional electricity trade creates mutual dependence: Any disruption of trade would affect the trade partners in the same way. This disincentivizes the abuse of energy trade for political purposes.

5.3 Demand flexibility

The IEA defines demand response as “balancing the demand on power grids by encouraging customers to shift electricity demand to times when electricity is more plentiful or other demand is lower, typically through prices or monetary incentives”. The literature distinguishes between demand response for residential and for industrial customers. The IEA highlights that several jurisdictions, including Australia, Brazil, the European Union and Korea already have legislation on demand response (IEA 2023b). Both residential and industrial demand response are encouraged in the legislation and some countries are already implementing it.

Residential demand response is based on smart devices, which receive a price signal from the utility and manage electricity consumption to minimize cost. Hence, it does not require active user management. A systematic review of demand respond pilots shows that households weigh financial benefits, cost, effort and perceived risk in their decision to participate (Parrish et al. 2020). Households with higher income, younger household members and households with suitable devices, like air conditioners, are more likely to participate (Wang et al. 2020). If consumer prices would reflect market prices at high frequency, cost savings would exceed the installation cost for smart meters, without loss for non-responding households (Blaschke 2022). In conclusion, residential demand response is feasible, even if not all households will choose to participate.

Industrial demand response is pioneered in the United States (Cappers, Goldman, and Kathan 2010) and Korea (Lee, Baek, and Kim 2022) and in a pilot in Shanghai, China (Chen et al. 2021). This highlights that governments recognize the potential and are willing to explore it, even though the share of renewable energy in most countries’ electricity mix is still low. A technical analysis shows that demand response is useful to balance short-term fluctuations, but does not to fully compensate renewable energy variability (Müller and Möst 2018). Nevertheless, Leinauer et al. (2022) identify both technical and economic obstacles to a more widespread adoption of industrial demand response. This can be expected to change when the share of renewable energy increases, as price differentials will increase and with it the possibility to derive profits and the willingness to resolve technical challenges.

5.4 Energy storage

Energy storage is the first thing that comes to mind in the context of variable energy supply from renewables. However, it should be used only when there is no cheaper option among the three other solutions discussed before. The most well-known form of energy storage is batteries. It is already profitable to use for short-term energy storage (Comello and Reichelstein 2019) and their use reduces the cost of generating electricity (Y.

Yang et al. 2018). In 2023, battery cost has hit another all-time low and is now 82% less expensive than in 2013.[9] As mentioned above, the price decline has caused a boom in battery investment in the US (eia 2024), which can be expected to enable further price decline. Long-term storage to balance demand and supply across seasons can complement the use of batteries. Options for this are pumping water into a reservoir, called pumped hydro storage, and compressed air energy storage, which saves energy in compressed air (Dowling et al. 2020).

A further technology, "power-to-gas", can be used both to store energy and to facilitate the decarbonization of other sectors than electricity. When an electricity system has a high share of solar and wind energy, it will produce more electricity than it can absorb whenever conditions for these two technologies are good. The excess electricity can then be used to produce green hydrogen, which can be used directly in industry or processed further to a fuel for aviation (Dray et al. 2022), shipping (Müller-Casseres et al. 2024) or heating. The technology is already economical when a moderate carbon price and support for power-to-gas technology is available in a country (Yilmaz et al. 2022). The gas could flow through existing natural gas pipelines once it is processed through a specific form of methanation (Romeo et al. 2022). It could also be used for electricity production in retrofitted gas power plants, but it can also be used directly or after further processing.

6. Conclusion

Reducing electricity sector emissions is a key macroeconomic challenge. This review finds that state-of-the-art energy-economy models identify solar and wind as the most important energy sources for decarbonizing electricity production. CCS, nuclear energy, biomass, and other types of renewable energy have a supporting role. This result is derived at a global level.[10] The global perspective is important, for example to ensure that total emissions stay within the global emission budget. The global perspective is also important to ensure that energy trade, via fuels or the electricity grid is consistent across regions. The insights need to be broken down to a local level to be useful to policymakers. A first step has been taken by considering the electricity mixes for some world regions. These show that mixes vary by region, but that all regions can rely on solar and wind power. For country level planning, country studies which are compatible with the global view can be used.

The discussion focused on the electricity sources used. Operationalizing these insights requires a deeper look at the results. The models discussed here, and similar models, include details on which flexibility options and how much of them is used. For example, they include results on how much needs to be invested in electricity grid extension and energy storage. These investments need to go along with the investments in solar and wind energy. The complementary capacity in nuclear energy needs to be maintained and limited capacity for biomass and CCS needs to be developed. Therefore, while the message of this paper is to expand solar and wind capacity rapidly, in practice this needs to be implemented in a balanced and locally customized way.

A final aspect is in the rapid change we observed in optimal decarbonization pathways. Within 10 years, the approach for decarbonization moved from a heavy reliance on CCS, nuclear energy, and biomass (Figure 3) to solar and wind energy as the first choice (Figure 2), which was possible because technological development in flexibility options means that there are now viable alternatives to the concept of "baseload". The shift in results over the last 10 years reflects that there is considerable uncertainty on the optimal future electricity system in the next decades. It is important to stay on top of research results. Nuclear fusion is expected to enter the

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[9] https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/

[10] Note that IAMs are highly detailed with respect to technologies and regions, even though they are global models. See https://www.iamcdocumentation.eu/ for an impression on the complexity represented in the three IAMs used for this paper.

picture, but not before 2050. One development that might affect future electricity system design is energy storage. New technologies, like compressed air or new battery technology might make it even easier to rely on solar and wind energy, but it remains highly uncertain which flexibility options will prove the most effective. Another development is sector coupling, where sustainable fuels produced from renewable energy can be used outside the electricity sector. This is not yet expected to happen at scale, but there is a large potential.

References

Amoah, Anthony, Rexford Kweku Asiama, Kofi Korle, and Edmund Kwablah. 2022. “Corruption: Is It a Bane to Renewable Energy Consumption in Africa?” *Energy Policy* 163 (April):112854. https://doi.org/10.1016/j.enpol.2022.112854.

Ayas, Ceren, and John Wiseman. 2022. “Exploring the Political Economy of Coal: Insights from Turkey.” In *The Political Economy of Coal*, 153–68. Routledge.

Banerjee, Nilanjana. 2023. “Biomass to Energy — an Analysis of Current Technologies, Prospects, and Challenges.” *BioEnergy Research* 16 (2): 683–716. https://doi.org/10.1007/s12155-022-10500-7.

Baranes, Edmond, Julien Jacqmin, and Jean-Christophe Poudou. 2017. “Non-Renewable and Intermittent Renewable Energy Sources: Friends and Foes?” *Energy Policy* 111 (December):58–67. https://doi.org/10.1016/j.enpol.2017.09.018.

Beiter, Philipp, Jérôme Guillet, Malte Jansen, Elizabeth Wilson, and Lena Kitzing. 2024. “The Enduring Role of Contracts for Difference in Risk Management and Market Creation for Renewables.” *Nature Energy* 9 (1): 20–26. https://doi.org/10.1038/s41560-023-01401-w.

Blaschke, Maximilian J. 2022. “Dynamic Pricing of Electricity: Enabling Demand Response in Domestic Households.” *Energy Policy* 164 (May):112878. https://doi.org/10.1016/j.enpol.2022.112878.

Boer, Lukas, Andrea Pescatori, and Martin Stuermer. 2024. “Energy Transition Metals: Bottleneck for Net-Zero Emissions?” *Journal of the European Economic Association* 22 (1): 200–229. https://doi.org/10.1093/jeea/jvad039.

Bogdanov, Dmitrii, Javier Farfan, Kristina Sadovskaia, Arman Aghahosseini, Michael Child, Ashish Gulagi, Ayobami Solomon Oyewo, Larissa de Souza Noel Simas Barbosa, and Christian Breyer. 2019. “Radical Transformation Pathway towards Sustainable Electricity via Evolutionary Steps.” *Nature Communications* 10 (1): 1077. https://doi.org/10.1038/s41467-019-08855-1.

Bogdanov, Dmitrii, Ashish Gulagi, Mahdi Fasihi, and Christian Breyer. 2021. “Full Energy Sector Transition towards 100% Renewable Energy Supply: Integrating Power, Heat, Transport and Industry Sectors Including Desalination.” *Applied Energy* 283 (February):116273. https://doi.org/10.1016/j.apenergy.2020.116273.

Böhringer, Christoph, Sonja Peterson, Thomas F. Rutherford, Jan Schneider, and Malte Winkler. 2021. “Climate Policies after Paris: Pledge, Trade and Recycle: Insights from the 36th Energy Modeling Forum Study (EMF36).” *Energy Economics* 103 (November):105471. https://doi.org/10.1016/j.eneco.2021.105471.

Böse, Fanny, Alexander Wimmers, Björn Steigerwald, and Christian von Hirschhausen. 2024. “Questioning Nuclear Scale-up Propositions: Availability and Economic Prospects of Light Water, Small Modular and Advanced Reactor Technologies.” *Energy Research & Social Science* 110 (April):103448. https://doi.org/10.1016/j.erss.2024.103448.

Cappers, Peter, Charles Goldman, and David Kathan. 2010. “Demand Response in U.S. Electricity Markets: Empirical Evidence.” *Demand Response Resources: The US and International Experience* 35 (4): 1526–35. https://doi.org/10.1016/j.energy.2009.06.029.

Chen, Yongbao, Lixin Zhang, Peng Xu, and Alessandra Di Gangi. 2021. “Electricity Demand Response Schemes in China: Pilot Study and Future Outlook.” *Energy* 224 (June):120042. https://doi.org/10.1016/j.energy.2021.120042.

Child, Michael, Claudia Kemfert, Dmitrii Bogdanov, and Christian Breyer. 2019. “Flexible Electricity Generation, Grid Exchange and Storage for the Transition to a 100%

Renewable Energy System in Europe." *Renewable Energy* 139 (August):80–101. https://doi.org/10.1016/j.renene.2019.02.077.

Cho, Adrian. 2023. "Deal to Build Pint-Size Nuclear Reactors Is Canceled." *Science* 382 (6672): 749–50.

Comello, Stephen, and Stefan Reichelstein. 2019. "The Emergence of Cost Effective Battery Storage." *Nature Communications* 10 (1): 2038. https://doi.org/10.1038/s41467-019-09988-z.

Creutzig, Felix, Peter Agoston, Jan Christoph Goldschmidt, Gunnar Luderer, Gregory Nemet, and Robert C. Pietzcker. 2017. "The Underestimated Potential of Solar Energy to Mitigate Climate Change." *Nature Energy* 2 (9): 17140. https://doi.org/10.1038/nenergy.2017.140.

Cruz, Marco R.M., Desta Z. Fitiwi, Sérgio F. Santos, and João P.S. Catalão. 2018. "A Comprehensive Survey of Flexibility Options for Supporting the Low-Carbon Energy Future." *Renewable and Sustainable Energy Reviews* 97 (December):338–53. https://doi.org/10.1016/j.rser.2018.08.028.

Daioglou, Vassilis, Jonathan C. Doelman, Birka Wicke, Andre Faaij, and Detlef P. van Vuuren. 2019. "Integrated Assessment of Biomass Supply and Demand in Climate Change Mitigation Scenarios." *Global Environmental Change* 54 (January):88–101. https://doi.org/10.1016/j.gloenvcha.2018.11.012.

Dimanchev, Emil G., Joshua L. Hodge, and John E. Parsons. 2021. "The Role of Hydropower Reservoirs in Deep Decarbonization Policy." *Energy Policy* 155 (August):112369. https://doi.org/10.1016/j.enpol.2021.112369.

Dowling, Jacqueline A., Katherine Z. Rinaldi, Tyler H. Ruggles, Steven J. Davis, Mengyao Yuan, Fan Tong, Nathan S. Lewis, and Ken Caldeira. 2020. "Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems." *Joule* 4 (9): 1907–28. https://doi.org/10.1016/j.joule.2020.07.007.

Dray, Lynnette, Andreas W. Schäfer, Carla Grobler, Christoph Falter, Florian Allroggen, Marc E. J. Stettler, and Steven R. H. Barrett. 2022. "Cost and Emissions Pathways towards Net-Zero Climate Impacts in Aviation." *Nature Climate Change* 12 (10): 956–62. https://doi.org/10.1038/s41558-022-01485-4.

eia. 2024. "U.S. Battery Storage Capacity Expected to Nearly Double in 2024." U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=61202.

Fuhrman, Jay, Candelaria Bergero, Maridee Weber, Seth Monteith, Frances M. Wang, Andres F. Clarens, Scott C. Doney, William Shobe, and Haewon McJeon. 2023. "Diverse Carbon Dioxide Removal Approaches Could Reduce Impacts on the Energy–Water–Land System." *Nature Climate Change* 13 (4): 341–50. https://doi.org/10.1038/s41558-023-01604-9.

Fuhrman, Jay, Simone Speizer, Patrick O'Rourke, Glen P Peters, Haewon McJeon, Seth Monteith, Laura Aldrete Lopez, and Frances M Wang. 2024. "Ambitious Efforts on Residual Emissions Can Reduce CO2 Removal and Lower Peak Temperatures in a Net-Zero Future." *Environmental Research Letters* 19 (6): 064012. https://doi.org/10.1088/1748-9326/ad456d.

Fuss, Sabine, William F Lamb, Max W Callaghan, Jérôme Hilaire, Felix Creutzig, Thorben Amann, Tim Beringer, et al. 2018. "Negative Emissions—Part 2: Costs, Potentials and Side Effects." *Environmental Research Letters* 13 (6): 063002. https://doi.org/10.1088/1748-9326/aabf9f.

Gabriel, Sophie, Anne Baschwitz, Gilles Mathonnière, Florian Fizaine, and Tommy Eleouet. 2013. "Building Future Nuclear Power Fleets: The Available Uranium Resources

Constraint." *Resources Policy* 38 (4): 458–69. https://doi.org/10.1016/j.resourpol.2013.06.008.

Guivarch, Céline, Thomas Le Gallic, Nico Bauer, Panagiotis Fragkos, Daniel Huppmann, Marc Jaxa-Rozen, Ilkka Keppo, et al. 2022. "Using Large Ensembles of Climate Change Mitigation Scenarios for Robust Insights." *Nature Climate Change* 12 (5): 428–35. https://doi.org/10.1038/s41558-022-01349-x.

Gürsan, C., and V. de Gooyert. 2021. "The Systemic Impact of a Transition Fuel: Does Natural Gas Help or Hinder the Energy Transition?" *Renewable and Sustainable Energy Reviews* 138 (March):110552. https://doi.org/10.1016/j.rser.2020.110552.

Haegel, Nancy M., Harry Atwater, Teresa Barnes, Christian Breyer, Anthony Burrell, Yet-Ming Chiang, Stefaan De Wolf, et al. 2019. "Terawatt-Scale Photovoltaics: Transform Global Energy." *Science* 364 (6443): 836. https://doi.org/10.1126/science.aaw1845.

Hansen, Kenneth, Christian Breyer, and Henrik Lund. 2019. "Status and Perspectives on 100% Renewable Energy Systems." *Energy* 175 (May):471–80. https://doi.org/10.1016/j.energy.2019.03.092.

Hanssen, Steef, V. Daioglou, Z. J. N. Steinmann, J. C. Doelman, D. P. Van Vuuren, and M. A. J. Huijbregts. 2020. "The Climate Change Mitigation Potential of Bioenergy with Carbon Capture and Storage." *Nature Climate Change* 10 (11): 1023–29. https://doi.org/10.1038/s41558-020-0885-y.

Hanssen, Steef, Vassilis Daioglou, Zoran J. N. Steinmann, Stefan Frank, Alexander Popp, Thierry Brunelle, Pekka Lauri, Tomoko Hasegawa, Mark A. J. Huijbregts, and Detlef P. Van Vuuren. 2020. "Biomass Residues as Twenty-First Century Bioenergy Feedstock—a Comparison of Eight Integrated Assessment Models." *Climatic Change* 163 (3): 1569–86. https://doi.org/10.1007/s10584-019-02539-x.

Hanto, Jonathan, Akira Schroth, Lukas Krawielicki, Pao-Yu Oei, and Jesse Burton. 2022. "16 The Political Economy of Energy and Climate Policy in South Africa." *The Political Economy of Coal*, 300.

Hepburn, Cameron, Ella Adlen, John Beddington, Emily A. Carter, Sabine Fuss, Niall Mac Dowell, Jan C. Minx, Pete Smith, and Charlotte K. Williams. 2019. "The Technological and Economic Prospects for CO2 Utilization and Removal." *Nature* 575 (7781): 87–97. https://doi.org/10.1038/s41586-019-1681-6.

Hickmann, Thomas, Christoph Bertram, Frank Biermann, Elina Brutschin, Elmar Kriegler, Jasmine E. Livingston, Silvia Pianta, Keywan Riahi, Bas van Ruijven, and Detlef van Vuuren. 2022. "Exploring Global Climate Policy Futures and Their Representation in Integrated Assessment Models." *Politics and Governance; Vol 10, No 3 (2022): Exploring Climate Policy Ambition*. https://doi.org/10.17645/pag.v10i3.5328.

Humpenöder, Florian, Alexander Popp, Leon Merfort, Gunnar Luderer, Isabelle Weindl, Benjamin Leon Bodirsky, Miodrag Stevanović, et al. 2024. "Food Matters: Dietary Shifts Increase the Feasibility of 1.5°C Pathways in Line with the Paris Agreement." *Science Advances* 10 (13): eadj3832. https://doi.org/10.1126/sciadv.adj3832.

IEA. 2015. "World Energy Outlook 2015." Paris: International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2015.

———. 2021a. "Net Zero by 2050 A Roadmap for the Global Energy Sector." Paris: International Energy Agency. https://www.iea.org/reports/net-zero-by-2050.

———. 2021b. "Renewables 2021." Paris: International Energy Agency. https://www.iea.org/reports/renewables-2021.

———. 2022a. "Nuclear Power and Secure Energy Transitions." Paris: International Energy Agency. https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions.

———. 2022b. “Nuclear Power Capacity Additions and Retirements in Selected Countries and Regions by Decade in the Net Zero Scenario.” Paris: International Energy Agency. https://www.iea.org/data-and-statistics/charts/nuclear-power-capacity-additions-and-retirements-in-selected-countries-and-regions-by-decade-in-the-net-zero-scenario.

———. 2023a. “Investment Spending on Electricity Grids, 2015-2022.” Paris: International Energy Agency. https://www.iea.org/data-and-statistics/charts/investment-spending-on-electricity-grids-2015-2022.

———. 2023b. “Tracking Clean Energy Progress 2023.” Paris: International Energy Agency. https://www.iea.org/reports/tracking-clean-energy-progress-2023.

———. 2024. “Renewables 2023.” Paris: International Energy Agency. https://www.iea.org/reports/renewables-2023.

IMF. 2023. “Global Financial Stability Report: Financial and Climate Policies for a High-Interest-Rate Era.” International Monetary Fund. https://www.imf.org/en/Publications/GFSR/Issues/2023/10/10/global-financial-stability-report-october-2023.

IRENA. 2023. “Renewable Power Generation Costs in 2022.” International Renewable Energy Agency. https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022.

———. 2024. “The Global Atlas for Renewable Energy: A Decade in the Making.” Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/Publications/2024/Apr/The-Global-Atlas-for-Renewable-Energy-A-decade-in-the-making.

IRENA and CPI. 2023. “Global Landscape of Renewable Energy Finance 2023.” Abu Dhabi: International Renewable Energy Agency. https://www.irena.org/Publications/2023/Feb/Global-landscape-of-renewable-energy-finance-2023.

Jeswani, Harish K., Andrew Chilvers, and Adisa Azapagic. 2020. “Environmental Sustainability of Biofuels: A Review.” *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 476 (2243): 20200351. https://doi.org/10.1098/rspa.2020.0351.

Jolie, Egbert, Samuel Scott, James Faulds, Isabelle Chambefort, Guðni Axelsson, Luis Carlos Gutiérrez-Negrín, Simona Regenspurg, et al. 2021. “Geological Controls on Geothermal Resources for Power Generation.” *Nature Reviews Earth & Environment* 2 (5): 324–39. https://doi.org/10.1038/s43017-021-00154-y.

Kemfert, Claudia, Fabian Präger, Isabell Braunger, Franziska M. Hoffart, and Hanna Brauers. 2022. “The Expansion of Natural Gas Infrastructure Puts Energy Transitions at Risk.” *Nature Energy* 7 (7): 582–87. https://doi.org/10.1038/s41560-022-01060-3.

Kim, Jaden, Augustus Panton, and Gregor Schwerhoff. 2024. “Energy Security and the Green Transition.” *IMF Working Papers* 2024 (006). https://www.imf.org/en/Publications/WP/Issues/2024/01/12/Energy-Security-and-The-Green-Transition-543806.

Klimenko, V. V., A. G. Tereshin, and O. V. Mikushina. 2009. “Global Energy and Climate of the Planet in the XXI Century in the Context of Historical Trends.” *Russian Journal of General Chemistry* 79 (11): 2469–76. https://doi.org/10.1134/S1070363209110358.

Krall, Lindsay M., Allison M. Macfarlane, and Rodney C. Ewing. 2022. “Nuclear Waste from Small Modular Reactors.” *Proceedings of the National Academy of Sciences* 119 (23): e2111833119. https://doi.org/10.1073/pnas.2111833119.

Laureto, John J., and Joshua M. Pearce. 2016. “Nuclear Insurance Subsidies Cost from Post-Fukushima Accounting Based on Media Sources.” *Sustainability* 8 (12). https://doi.org/10.3390/su8121301.

Lee, Eunjung, Keon Baek, and Jinho Kim. 2022. “Datasets on South Korean Manufacturing Factories’ Electricity Consumption and Demand Response Participation.” *Scientific Data* 9 (1): 227. https://doi.org/10.1038/s41597-022-01357-8.

Leinauer, Christina, Paul Schott, Gilbert Fridgen, Robert Keller, Philipp Ollig, and Martin Weibelzahl. 2022. “Obstacles to Demand Response: Why Industrial Companies Do Not Adapt Their Power Consumption to Volatile Power Generation.” *Energy Policy* 165 (June):112876. https://doi.org/10.1016/j.enpol.2022.112876.

L’Her, G. F., R. S. Kemp, M. D. Bazilian, and M. R. Deinert. 2024. “Potential for Small and Micro Modular Reactors to Electrify Developing Regions.” *Nature Energy*, April. https://doi.org/10.1038/s41560-024-01512-y.

Lovering, Jessica R., Arthur Yip, and Ted Nordhaus. 2016. “Historical Construction Costs of Global Nuclear Power Reactors.” *Energy Policy* 91 (April):371–82. https://doi.org/10.1016/j.enpol.2016.01.011.

Lu, Tianguang, Peter Sherman, Xinyu Chen, Shi Chen, Xi Lu, and Michael McElroy. 2020. “India’s Potential for Integrating Solar and on- and Offshore Wind Power into Its Energy System.” *Nature Communications* 11 (1): 4750. https://doi.org/10.1038/s41467-020-18318-7.

Luderer, Gunnar, Silvia Madeddu, Leon Merfort, Falko Ueckerdt, Michaja Pehl, Robert Pietzcker, Marianna Rottoli, et al. 2022. “Impact of Declining Renewable Energy Costs on Electrification in Low-Emission Scenarios.” *Nature Energy* 7 (1): 32–42. https://doi.org/10.1038/s41560-021-00937-z.

Mayfield, Erin N., Jared L. Cohon, Nicholas Z. Muller, Inês M. L. Azevedo, and Allen L. Robinson. 2019. “Cumulative Environmental and Employment Impacts of the Shale Gas Boom.” *Nature Sustainability* 2 (12): 1122–31. https://doi.org/10.1038/s41893-019-0420-1.

MITei. 2018. “Https://Energy.Mit.Edu/Research/Future-Nuclear-Energy-Carbon-Constrained-World/.” MIT Energy Initiative. https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/.

Mitri, Maria Eugenia, Sofia Maia, Ana Paula Fonseca Teixeira, and Laura Foroni. 2023. “Climatescope 2023 Power Transition Factbook.” BloombergNEF. https://www.global-climatescope.org/.

Monnet, Antoine, Sophie Gabriel, and Jacques Percebois. 2017. “Analysis of the Long-Term Availability of Uranium: The Influence of Dynamic Constraints and Market Competition.” *Energy Policy* 105 (June):98–107. https://doi.org/10.1016/j.enpol.2017.02.010.

Montrone, Lorenzo, Nils Ohlendorf, and Rohit Chandra. 2021. “The Political Economy of Coal in India – Evidence from Expert Interviews.” *Energy for Sustainable Development* 61 (April):230–40. https://doi.org/10.1016/j.esd.2021.02.003.

Moriarty, Patrick, and Damon Honnery. 2012. “What Is the Global Potential for Renewable Energy?” *Renewable and Sustainable Energy Reviews* 16 (1): 244–52. https://doi.org/10.1016/j.rser.2011.07.151.

Muellner, Nikolaus, Nikolaus Arnold, Klaus Gufler, Wolfgang Kromp, Wolfgang Renneberg, and Wolfgang Liebert. 2021. “Nuclear Energy - The Solution to Climate Change?” *Energy Policy* 155 (August):112363. https://doi.org/10.1016/j.enpol.2021.112363.

Müller, Theresa, and Dominik Möst. 2018. “Demand Response Potential: Available When Needed?” *Energy Policy* 115 (April):181–98. https://doi.org/10.1016/j.enpol.2017.12.025.

Müller-Casseres, Eduardo, Florian Leblanc, Maarten van den Berg, Panagiotis Fragkos, Olivier Dessens, Hesam Naghash, Rebecca Draeger, et al. 2024. “International Shipping in a World below 2 °C.” *Nature Climate Change* 14 (6): 600–607. https://doi.org/10.1038/s41558-024-01997-1.

NGFS. 2023a. “NGFS Climate Scenarios Technical Documentation V4.2.” Network for Greening the Financial System. https://www.ngfs.net/en/ngfs-climate-scenarios-phase-iv-november-2023.

———. 2023b. “NGFS Scenarios for Central Banks and Supervisors.” Network for Greening the Financial System. https://www.ngfs.net/en/ngfs-climate-scenarios-phase-iv-november-2023.

Nicholas, T.E.G., T.P. Davis, F. Federici, J. Leland, B.S. Patel, C. Vincent, and S.H. Ward. 2021. “Re-Examining the Role of Nuclear Fusion in a Renewables-Based Energy Mix.” *Energy Policy* 149 (February):112043. https://doi.org/10.1016/j.enpol.2020.112043.

Nishiura, Osamu, Volker Krey, Oliver Fricko, Bas van Ruijven, and Shinichiro Fujimori. 2024. “Integration of Energy System and Computable General Equilibrium Models: An Approach Complementing Energy and Economic Representations for Mitigation Analysis.” *Energy* 296 (June):131039. https://doi.org/10.1016/j.energy.2024.131039.

Parrish, Bryony, Phil Heptonstall, Rob Gross, and Benjamin K. Sovacool. 2020. “A Systematic Review of Motivations, Enablers and Barriers for Consumer Engagement with Residential Demand Response.” *Energy Policy* 138 (March):111221. https://doi.org/10.1016/j.enpol.2019.111221.

Pietzcker, Robert C., Falko Ueckerdt, Samuel Carrara, Harmen Sytze de Boer, Jacques Després, Shinichiro Fujimori, Nils Johnson, et al. 2017. “System Integration of Wind and Solar Power in Integrated Assessment Models: A Cross-Model Evaluation of New Approaches.” *Energy Economics* 64 (May):583–99. https://doi.org/10.1016/j.eneco.2016.11.018.

Riahi, Keywan, Elmar Kriegler, Nils Johnson, Christoph Bertram, Michel den Elzen, Jiyong Eom, Michiel Schaeffer, et al. 2015. “Locked into Copenhagen Pledges — Implications of Short-Term Emission Targets for the Cost and Feasibility of Long-Term Climate Goals.” *Technological Forecasting and Social Change* 90 (January):8–23. https://doi.org/10.1016/j.techfore.2013.09.016.

Ricks, Wilson, Katharine Voller, Gerame Galban, Jack H. Norbeck, and Jesse D. Jenkins. 2024. “The Role of Flexible Geothermal Power in Decarbonized Electricity Systems.” *Nature Energy*, January. https://doi.org/10.1038/s41560-023-01437-y.

Romeo, Luis M., Marco Cavana, Manuel Bailera, Pierluigi Leone, Begoña Peña, and Pilar Lisbona. 2022. “Non-Stoichiometric Methanation as Strategy to Overcome the Limitations of Green Hydrogen Injection into the Natural Gas Grid.” *Applied Energy* 309 (March):118462. https://doi.org/10.1016/j.apenergy.2021.118462.

Sepulveda, Nestor A., Jesse D. Jenkins, Aurora Edington, Dharik S. Mallapragada, and Richard K. Lester. 2021. “The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems.” *Nature Energy* 6 (5): 506–16. https://doi.org/10.1038/s41560-021-00796-8.

Sepulveda, Nestor A., Jesse D. Jenkins, Fernando J. de Sisternes, and Richard K. Lester. 2018. “The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation.” *Joule* 2 (11): 2403–20. https://doi.org/10.1016/j.joule.2018.08.006.

Tomabechi, Ken. 2010. “Energy Resources in the Future.” *Energies* 3 (4): 686–95. https://doi.org/10.3390/en3040686.

Tröndle, Tim, Johan Lilliestam, Stefano Marelli, and Stefan Pfenninger. 2020. “Trade-Offs between Geographic Scale, Cost, and Infrastructure Requirements for Fully Renewable Electricity in Europe.” *Joule* 4 (9): 1929–48. https://doi.org/10.1016/j.joule.2020.07.018.

Ueckerdt, Falko, Robert Pietzcker, Yvonne Scholz, Daniel Stetter, Anastasis Giannousakis, and Gunnar Luderer. 2017. “Decarbonizing Global Power Supply under Region-Specific Consideration of Challenges and Options of Integrating Variable Renewables in the

REMIND Model." *Energy Economics* 64 (May):665–84. https://doi.org/10.1016/j.eneco.2016.05.012.

Vaya Soler, Antonio, Michel Berthelemy, Aditi Verma, Sama Bilbao y Leon, Gloria Kwong, Vladislav Sozoniuk, Andrew White, Veronique Rouyer, Kimberly Sexton Nick, and Ximena Vasquez-Maignan. 2021. "Small Modular Reactors: Challenges and Opportunities." Nuclear Energy Agency of the OECD (NEA). http://inis.iaea.org/search/search.aspx?orig_q=RN:52041043.

Victoria, Marta, Kun Zhu, Tom Brown, Gorm B. Andresen, and Martin Greiner. 2020. "Early Decarbonisation of the European Energy System Pays Off." *Nature Communications* 11 (1): 6223. https://doi.org/10.1038/s41467-020-20015-4.

Wang, Zhaohua, Hao Li, Nana Deng, Kaiwei Cheng, Bin Lu, Bin Zhang, and Bo Wang. 2020. "How to Effectively Implement an Incentive-Based Residential Electricity Demand Response Policy? Experience from Large-Scale Trials and Matching Questionnaires." *Energy Policy* 141 (June):111450. https://doi.org/10.1016/j.enpol.2020.111450.

Way, Rupert, Matthew C. Ives, Penny Mealy, and J. Doyne Farmer. 2022. "Empirically Grounded Technology Forecasts and the Energy Transition." *Joule* 6 (9): 2057–82. https://doi.org/10.1016/j.joule.2022.08.009.

Wealer, B., S. Bauer, C.v. Hirschhausen, C. Kemfert, and L. Göke. 2021. "Investing into Third Generation Nuclear Power Plants - Review of Recent Trends and Analysis of Future Investments Using Monte Carlo Simulation." *Renewable and Sustainable Energy Reviews* 143 (June):110836. https://doi.org/10.1016/j.rser.2021.110836.

Xu, Rongrong, Zhenzhong Zeng, Ming Pan, Alan D. Ziegler, Joseph Holden, Dominick V. Spracklen, Lee E. Brown, et al. 2023. "A Global-Scale Framework for Hydropower Development Incorporating Strict Environmental Constraints." *Nature Water* 1 (1): 113–22. https://doi.org/10.1038/s44221-022-00004-1.

Yang, Haozhe, Ranjit Deshmukh, and Sangwon Suh. 2023. "Global Transcontinental Power Pools for Low-Carbon Electricity." *Nature Communications* 14 (1): 8350. https://doi.org/10.1038/s41467-023-43723-z.

Yang, Yuqing, Stephen Bremner, Chris Menictas, and Merlinde Kay. 2018. "Battery Energy Storage System Size Determination in Renewable Energy Systems: A Review." *Renewable and Sustainable Energy Reviews* 91 (August):109–25. https://doi.org/10.1016/j.rser.2018.03.047.

Yilmaz, Hasan Ümitcan, Steven O. Kimbrough, Clemens van Dinther, and Dogan Keles. 2022. "Power-to-Gas: Decarbonization of the European Electricity System with Synthetic Methane." *Applied Energy* 323 (October):119538. https://doi.org/10.1016/j.apenergy.2022.119538.

Appendix: Background information for Section 2

Table A1: Overview of Models

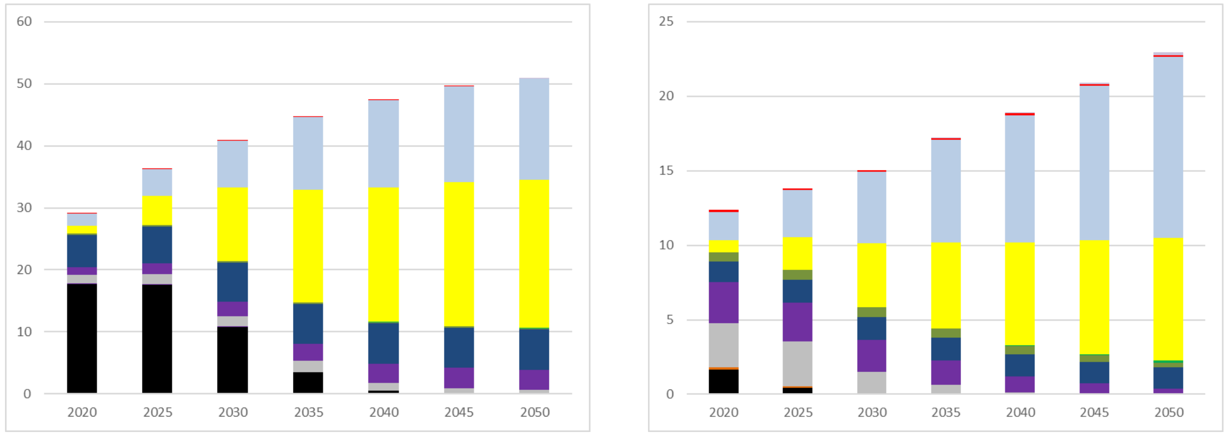
Model name	Hosting institution	URL	Sample publication
Global Change Assessment Model (GCAM) 6.0	Joint Global Change Research Institute in the United States	https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model	Fuhrman et al. (2024)
MESSAGEix-GLOBIOM 1.1-M-R12	International Institute for Applied Systems Analysis (IIASA)	https://docs.messageix.org/en/latest/	Nishiura et al. (2024)
REMIND-MAgPIE	Potsdam Institute for Climate Impact Research	https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind	Humpenöder et al. (2024)
World Energy Model	International Energy Agency	https://www.iea.org/reports/global-energy-and-climate-model	IEA (2021a)

Source: Author’s summary based on sources provided in table.

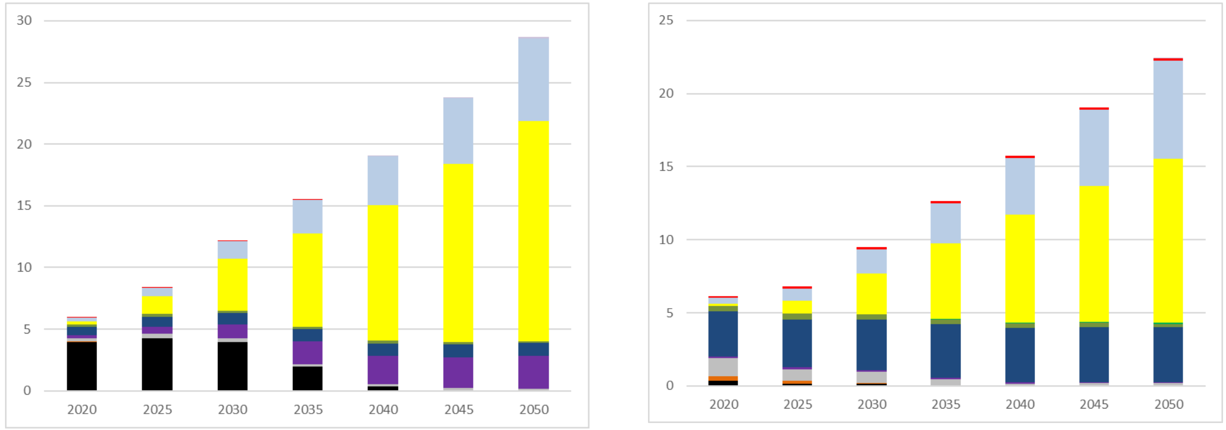
Note: This table complements the model introduction in Section 2.2..

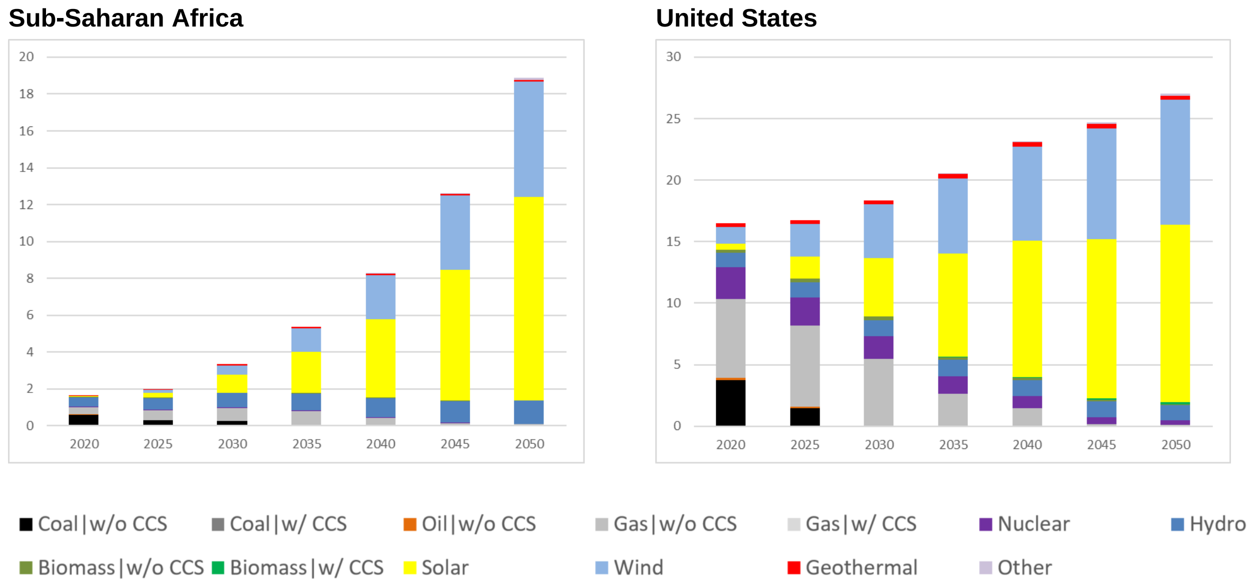
Figure A1: Model results across world regions

China **EU 28**



India **Latin America and the Caribbean**





Source: NGFS (2023)

Note: Model results are from the model REMIND-MAgPIE 3.2-4.6 and the scenario “below 2°C”. The model has 12 regions, six of which are selected here.

The electricity mix in the regions is determined by the conditions found in the region. One condition is the initial composition of the electricity mix, as reflected in historical data for 2020. In China and India, coal was the dominant source of electricity. In the EU and Sub-Saharan Africa, several energy sources are of similar importance. In Latin America and the Caribbean, hydropower had the largest share and in the United States, natural gas was a dominant source. Another key condition is the potential for renewable energy. The potential determines how regions are projected to specialize. India and Sub-Saharan Africa are projected to derive more than two thirds of their electricity production from solar energy by 2050, which reflects excellent solar potential in these regions. The EU has an exceptionally high share of wind energy, reflecting good wind potential. For a detailed overview of renewable energy sources, see the collection of maps on renewable energy in (IRENA 2024). Another condition is the production of renewable energy technology. China’s share in all manufacturing stages of the solar PV supply chain exceeds 80 percent. China is also the country with the largest share in wind turbine manufacturing.[11] While solar panels and wind turbines are traded in large volumes, domestic production capacity ensures access to low-cost supply.

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[11] https://about.bnef.com/blog/chinas-goldwind-retains-turbine-supplier-lead-as-global-wind-additions-hit-new-high-according-to-bloombergnef/

PUBLICATIONS