Energy and Climate Change 6 (2025) 100196

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

Evolving electricity supply and demand to achieve net-zero emissions: Insights from the EMF-37 study

Ruying Gao [a], Trieu Mai [b], Seyed Shahabeddin Mousavi [a,*], Charles Rossmann [c], Matthew Binsted [d], John Bistline [e], Geoff Blanford [e], Morgan Browning [f], Matthias Fripp [g], Patrick Lamers [b], Matteo Muratori [h], Sharon Showalter [i], John Weyant [a]

[a] *Stanford University, Management Science and Engineering, Palo Alto, CA, USA*
[b] *National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, USA 80401*
[c] *Southern Company, USA*
[d] *Joint Global Change Research Institute, College Park, MD, USA*
[e] *EPRI, Palo Alto, CA, USA*
[f] *US Environmental Protection Agency, 1200 Pennsylvania Ave NW, WA, DC, USA*
[g] *Environmental Defense Fund, USA*
[h] *Pacific Northwest National Laboratory, 902 Battelle Blvd, Richland, WA, USA*
[i] *OnLocation, Inc., Vienna, VA, USA*

ARTICLE INFO

Keywords:
Model comparison
Climate change
Deep decarbonization
Electrification
Energy systems

ABSTRACT

This paper explores the role of electricity in achieving economy-wide net-zero CO_2 emissions by 2050 in the United States based on results from 17 models as part of the 37th Stanford Energy Modeling Forum (EMF-37). In the study's Net-Zero scenario, the models use diverse pathways to achieve net-zero emissions by 2050, with gross energy-related residual emissions ranging from 17.2 to 66.6 % of 2020 levels. Electricity consistently emerges as central to achieving net-zero, with models projecting rapid electrification of end-uses and rapidly declining CO_2 intensity of electricity. However, the extent of electrification and the technology mix to decarbonize the power sector vary considerably across models. In the Net-Zero scenario, electricity is projected to evolve from ~20 % of final energy in 2020 to 17–63 % in 2050 across the models driven by electrification in all sectors—buildings, industry, and transportation—and, to a lesser extent by direct air capture. By 2050, total electricity consumption increases by 24–176 % (relative to 2020), accompanied by significant expansion in renewable electricity production. Together, solar and wind generation grows by 175–834 %, supplying 45–90 % of total electricity in 2050, with wind achieving slightly higher shares than solar. Electricity storage technologies are deployed at scale to support wind and solar generation. The electricity generation mix varies across models: some project almost complete reliance on renewables, while others see a substantial role for natural gas, often with carbon capture and storage. This paper synthesizes the rich diversity of modeling approaches and results, highlighting differing views on how key drivers of electricity demand and supply might evolve.

1. Introduction

Emissions reduction targets, set by many governments and industry, have become increasingly ambitious. The United States, for example, in 2021 set a goal of net-zero economy-wide greenhouse gas emissions by 2050 [1] and carbon-free electricity generation by 2035 [2]. Analysis with energy system models is often used to inform the targets and the pathways to achieving them. Study number 37 by the Stanford Energy Modeling Forum (EMF-37) continues the long tradition of convening international working groups of modelers and model users in energy, economics, and the environment. In this case, it brought together 17 modeling teams to analyze deep decarbonization and high electrification for the U.S. energy system (see Browning et al. for an overview of EMF-37) [3].

Energy system models have a wide variety of structures and underlying logic. Analyses done with such models can also vary in the assumptions adopted by a modeling team regarding future technology, market and policy conditions, and myriad other factors, largely

* Corresponding author.
E-mail addresses: ssmousav@cs.stanford.edu, ssmousav@stanford.edu (S.S. Mousavi).

https://doi.org/10.1016/j.egycc.2025.100196

Available online 5 May 2025

reflecting uncertainties about how these key elements of the energy system will evolve in the years ahead. This paper is one of several cross-cut papers presenting insights from the analyses conducted as part of the overall EMF-37 study and focuses on the role of the electricity sector under net-zero emissions futures.

The electricity sector plays a unique role in the energy system. Today, electricity provides about 20 % of total final energy use in the United States. Currently, in the U.S., electricity consumption comprises about 50 % of total final energy consumption in residential and commercial buildings and about a 15 % share in industry. The U.S. transportation sector relies on electricity for less than 1 % of its energy needs today, but the rapid adoption of electric vehicles (EVs) is increasing the degree of transportation electrification [4]. Over the past two decades, the U.S. electricity supply system has also undergone substantial changes that include transitioning from coal-fueled generation to lower-emissions technologies, especially natural gas, solar, and wind, while nuclear and hydro generation remain stable. As a result, annual carbon dioxide (CO_2) emissions from electricity generation in 2022 were about 40 % lower than in 2005. Electricity generation is no longer the largest source of emissions as it was for much of the past century; transportation is now the largest source of GHG emissions in the United States. Nonetheless, substantial emissions from power generation remain, and there are important uncertainties about further reductions.

The decarbonization of electricity production and decarbonization of the overall economy are interrelated. Key questions about electricity system evolution under decarbonization futures include:

- **Pace of decarbonization.** When and by how much do CO_2 emissions associated with electricity production and overall energy use decrease?
- **Electricity's role.** How is electricity used in the U.S. economy? What share of total energy consumption will be supplied by electricity? How does this share change with decarbonization? To what extent is decarbonization of other sectors accomplished by electrifying end uses?
- **Electricity production.** Among the low-emissions sources of electricity generation, which are anticipated to play larger roles? What other electricity system changes are needed to transition to a decarbonized electricity grid?

In this paper, we explore the role of electricity in achieving net-zero emissions in the U.S. energy system across the participating models and scenarios from the EMF-37 study. Specifically, we examine reductions in emissions from electricity production, the transformation of electricity systems, and the extent of electrification across sectors. We also explore the extent to which electrification–either directly or indirectly–increases electricity generation. Finally, we present the models' projected changes to electricity supply to meet these changes in electricity demand and reductions in emissions.

As with the broader EMF-37 study, our model comparison focusing on electricity is intended to find areas of consensus and highlight key differences among the participating models. In particular, this model comparison exercise did not attempt to harmonize all inputs. Instead, it recognizes–and embraces–the rich diversity of approaches and lessons in electricity modeling and differences of opinion about how the key drivers of electricity use might evolve. By characterizing the impact that varying modeling decisions and key uncertainties can have on outputs of interest, we hope to reveal areas where model results differ and deserve further study. We also hope to help decision-makers increase their familiarity with "robust" approaches that make sense across many views and to leverage modeling insights in a way that is consistent with their risk appetite. Operationally, the EMF-37 study specified emissions reduction targets in the Net-Zero scenario (described below) and provided detailed guidance for macroeconomic assumptions in accordance with the EIA's Annual Energy Outlook [5]. Browning et al. [3] describe the structure of the EMF-37 study, which includes several papers focused on other cross-cutting topics in addition to this electricity-focused one. Under these predefined conditions, differences in model projections are the result of differences in models as well as assumptions about future technology costs, fuel prices, and other parameters. By comparing results from a wide variety of energy models comprehensively and systematically under multiple scenarios, this study illuminates the collective understanding of a broad spectrum of energy modelers as well as the key gaps and uncertainties among leading experts.

2. Scenarios, study design, and models

The EMF-37 study included several scenarios; in this paper, we consider only the two primary ones (Table 2.1): a Reference scenario and a Net-Zero CO_2 by 2050 (Net-Zero) scenario. Browning et al. [3] describe these two scenarios, as well as several additional ones from the overall EMF-37 study. Below is a summary description of the two scenarios considered in this paper.

2.1. The reference scenario

The Reference scenario assumes no new climate policy after early 2022. For the U.S., this excludes the measures in the Bipartisan Infrastructure Law (BIL), the Inflation Reduction Act of 2022 (IRA), and the standards and guidelines the Environmental Protection Agency (EPA) proposed in May 2023 under Section 111 of the Clean Air Act (111). To the extent practicable, the Reference scenario includes all other federal and state policies in place as of early 2022 (e.g. renewable portfolio standards, clean energy standards, the Regional Greenhouse Gas Initiative, and California's Global Warming Solutions Act of 2006 [AB32]). Modelers developed their own reference parameters to be consistent with the assumption of no new climate policies. Gross domestic product and population are important drivers of energy and emissions, and for this scenario, the modelers were encouraged to harmonize with assumptions from the EIA's Annual Energy Outlook 2022 Reference case [3].

The Reference scenario serves two functions in this study. First, it provides the modeling teams' perspective on the future evolution of the economy and energy systems. Second, it serves as a benchmark for comparison with the Net-Zero scenario.

The omission of IRA's energy and climate provisions impacts the Reference scenario projections. A recent model comparison exercise assessed the potential impacts of IRA on electrification, power sector decarbonization, and costs [6,7]. The 11-model comparison indicates that electric sector CO_2 reductions under IRA span 66–87 % below 2005 by 2035, compared with 39–68 % without IRA. The Net-Zero scenario, which is of primary focus in our analysis and is described in Section 2.2, is less impacted by IRA, therefore the policy's omission does not significantly affect study outcomes.

2.2. Net-Zero scenario

For this scenario, the national emission reduction pathway is defined as a linear CO_2 emission reduction from 2020 to net-zero emissions by 2050. The targets are specified as CO_2-only and include the following source and sink categories: fossil fuel combustion, net emissions from non-energy use of fossil fuels, industrial process emissions, carbon dioxide removal (CDR) technologies including direct air capture with storage (DACS), bio-energy with carbon capture and storage (BECCS), and natural carbon management options such as land use, land use change, and forestry (LULUCF). The Net-Zero scenario uses each model's default assumptions for technology costs, complementary policies, and consumer preferences.

For models in this study without endogenous estimates of natural carbon sinks, the net-zero annual emissions targets are converted into gross fossil fuel and industrial process CO_2 emission targets, and a constant sink of 800 $MtCO_2$ per year is assumed.[1] While the emissions pathways are specified as CO_2-only, models assume that the resulting carbon price or shadow price on carbon would also be applied to non-CO_2 GHGs as considered in each model.

Additional specifications to facilitate model comparability across the models in the Net-Zero scenario are as follows:

Revenue Recycling: For models that return revenue from emissions pricing instruments to consumers (i.e., computable general equilibrium models), a lump sum distribution is used to increase consistency across models and aid the consistency of distributional analyses.

Banking and Borrowing: The banking or borrowing of emissions was not allowed to meet the reduction targets. While allowing full flexibility with banking and borrowing may be more efficient, it would obscure some of the key issues we want to explore in this study, such as how the energy system would need to be configured to achieve net-zero emissions in the target year.

International Policy Outside of North America: The focus of this study is on decarbonization scenarios for North America. To minimize the trade effects in global models or models that represent international trade, we assume that all regions face the same carbon price–namely, the marginal cost of abating an additional ton, as found in the United States and Canada, which faces a quantity-based constraint.

Offsets: These scenarios assume no compliance option via offsets from activities, sectors, or countries outside of the cap.

2.3. Caveats and limitations

Several observations are relevant for the interpretation of these scenarios. The Reference and Net-Zero scenarios rely upon each model's default parameterization and assumptions. For example, the modelers had discretion over underlying drivers of energy and emissions such as population and economic growth, technology costs, energy substitution, and the price responsiveness of demand. The Reference scenario encapsulates differing views across the modeling teams regarding the evolution of energy consumption and emissions without additional climate policies. The Net-Zero scenario adds an emissions reduction constraint and represents the modeling teams' views about decarbonization, and the associated cost and availability of electrification, mitigation, and carbon removal options. This paper focuses on these two scenarios; a broader range of sensitivities—including different assumptions for clean energy technologies, consumer behavior, and other factors—are considered elsewhere in the EMF-37 study. Limited harmonization across models and the focus on a narrow set of scenarios are important features. Our objective is to identify common trends and differences among the numerous models as a group rather than assessing specific drivers associated with each model. Overall, these results represent possible outcomes and should not be interpreted as probability distributions or a full range of possible outcomes.

2.4. Models

The 17 models whose results are considered in this paper span a spectrum of spatial, sectoral, and technological detail; partial and general equilibrium approaches; myopic and perfect foresight; as well as optimization and simulation frameworks. All but one of the models represent the entire U.S. energy system; ReEDS is the exception as it is an electric sector-only model.[2] Table 1 provides details on the electricity characteristics of these 17 models. For additional details on these models—including spatial resolution, greenhouse gasses tracked, the equilibrium approach used, time step and time period, carbon management options, and the representation of energy use in buildings, industry, and transport see Table 2 in Browning et al. [3]. Note that although most of the 17 models have some level of regional disaggregation (see Table 1), this paper reports only aggregate U.S. results. This

Table 1
Summary characteristics of models participating in EMF-37. Technologies refer to electricity generation and storage technologies, and include retrofit options. Regions cover the primary U.S. grid network where load and generation are balanced. Time periods refer to how each annual period is resolved in the main dispatch models. Note that models can have subcategories for technologies, regions, and time periods that provide additional resolution.

Model name	Abbrev.	Institution	Electricity production granularity
Applied Dynamic Analysis of the Global Economy	ADAGE	RTI International	11 technologies
AnyMOD	AnyMOD	TU Berlin	36 technologies; 49 regions
Environment Canada's Multi-sector, Multi-regional Computable General Equilibrium (CGE) Model	EC-MSMR	Environment and Climate Change Canada	13 technologies including backstops; 17 regions
EnergyPATHWAYS/ Regional Investment and Operations Platform	EP-RIO	Evolved Energy Research	62 technologies; 27 regions; 960 time periods
EPA Integrated MARKAL-EFOM System Model	EPA-TIMES	USEPA/ORD	24 technologies; 9 U.S. regions
Energy Policy Simulator	EPS	Energy Innovation	16 technologies; 1 region
Future Agricultural Resources Model	FARM	USDA	10 technologies; 1 region
Office of Fossil Energy and Carbon Management National Energy Modeling System	FECM-NEMS	OnLocation	27 technologies; 25 regions
Global Change Analysis Model	GCAM	PNNL	23 technologies
Global Change Analysis Model - USA	GCAM-USA	PNNL	23 technologies; 15 regions; 4 time periods
gTech	gTech	Navius Research	16 technologies; 11 regions
Market and Allocation	MARKAL-NETL	NETL	45 technologies; 9 regions
North American Times Energy Model	NATEM	Esmia Consultants	90 technologies; 12 regions
Regional Energy Deployment System Model	ReEDS	NREL	85 technologies; 134 regions; 17 time periods
Tools for Energy Model Optimization and Analysis	TEMOA	NC State	18 technologies; 9 regions
U.S. Regional Economy, Greenhouse Gas, and Energy Model	US-REGEN	EPRI	94 technologies; 16 regions; 120 time periods
U.S. Regional Energy Model/Regional Energy Deployment System Model	USREP-ReEDS	MIT, NREL	58 technologies; 134 regions; 17 time periods

[1] Converting the net emissions goals to goals framed as a reduction in gross fossil carbon emissions requires consideration of the full array of U.S. GHG sources and sinks. This assumption provides 800 Mt CO_2 per year head room for models to reach the net-zero targets and translates into a maximum reduction of combustion and non-combustion CO_2 emissions of 87% in 2050.

[2] Note that the main scenarios from ReEDS are from Denholm et al. (2022).

is chiefly because the regions used by the individual models are not similar enough to make subnational comparisons useful.

Results are reported for all 17 models when available. Where data are not available (either because the specific aspects are not modeled or results are not reported) we exclude the model from our reporting. Although models do not explicitly harmonize technology cost and performance assumptions, a recent multi-model study of power sector impacts of the Inflation Reduction Act indicates that many U.S. models (including several in this study) use assumptions from NREL's Annual Technology Baseline or similar values[3] [8].

3. Results

3.1. Emission projections

We assess the pace of decarbonization and the extent to which CO_2 emissions associated with electricity production and overall energy use decrease across the models.

Fig. 1 illustrates paths of CO_2 emissions for the period 2020–2050 for both the Reference and Net-Zero scenarios. In the Reference scenario, most models project relatively flat emissions over the period 2020–2050. The lack of emissions growth in the Reference scenario is noteworthy because most models assume robust economic growth. This is consistent with models recognizing meaningful reductions in the emissions associated with economic activity over this period, even absent the pressure on CO_2 emissions applied in the Net-Zero scenario. Some models project large emissions reductions even in the Reference scenario, including ADAGE, US-REGEN and AnyMOD which project decreases by more than 20 % over the period. On the other hand, some models project small increases in gross energy emissions in the Reference scenario, including FECM-NEMS and EC-MSMR. Note that the flat emissions trend in the Reference differs from scenarios with IRA, where economy-wide emissions by a number of modeling teams are projected to decline by 43–48 % by 2035 from 2005, and electricity emissions to drop 66–87 % [9].

In the Net-Zero scenario, all models attempt to reach economy-wide net-zero CO_2 emissions in 2050. In this scenario, positive emissions from energy use or industrial processes can be netted to zero via carbon dioxide removal (CDR) approaches (also called negative emissions). For each model, projected net energy emissions in 2050 include any remaining emissions after accounting for offsets from negative emission activities. Across the models, the amount of negative-emission activities varies widely from 800 million metric tons (the study default assumption for terrestrial sequestration) to about 3 billion metric tons of CO_2 per year. Binsted et al. [10] describe the role of carbon dioxide removal technologies in the EMF-37 study in more detail.

All models show significant reductions in net emissions from 2020 to 2050 in the Net-Zero scenario. The projected gross reductions differ across the models from about 30 % reduction for FECM-NEMS to about 80 % for USREP-ReEDS, with the balance required to get to a 100 % reduction in CO_2 emissions to CDR which plays a vastly different role across models (CDR is also not consistently modeled in terms of technology options across models). The reduction across models ranges from 33.4 % to 82.8 %, the Net Zero scenario consistently shows much deeper reductions across all emission types, the electricity sector shows the largest reductions in the Reference scenario, and model agreement is much higher in the Net Zero scenario. Net emissions show the most dramatic differences between scenarios and most models achieve negative or near-zero emissions in the Net Zero scenario, with the spread between models being much smaller in the Net Zero scenario.

Emissions from the production of electricity are illustrated in the bottom row of Fig. 1. As with total *energy*-related emissions, most models project little change in electricity annual CO_2 emissions over the period 2020–2050 under the Reference scenario. Similarly, the lack of increase in emissions is noteworthy because electricity production in the Reference case increases by 9–189 % across models over this period. This means that in most models, electricity production relies increasingly on less-emitting approaches, even in the Reference scenario. In the Net-Zero scenario, all models project significant reductions in direct CO_2 emissions for electricity production. In many of the models, the bulk of the reduction over the period 2020–2050 is projected to happen by 2035, much faster than overall emissions reductions. This common trend suggests that lowering grid emissions could be an easier and/or earlier step for broader decarbonization, and a process that has been underway for some time, consistent with recent historical trends.

Fig. 2 illustrates the relationship in the model projections between the net point source CO_2 emissions intensity during electricity production (horizontal axis) and the change in overall CO_2 emissions in the U.S. in 2050 relative to 2020. The green markers are associated with results for 2050 in the Reference scenario. Their orientation along a northeast-southwest axis suggests that across these models, lower CO_2-intensive electricity production is consistent with greater 2050 emissions reductions (relative to 2020), even in the Reference case. The blue markers are associated with results for 2050 in the Net-Zero scenario. Their nearly vertical placement suggests that across these models, low-CO_2-intensive electricity production is expected by all models, even though they differ with respect to the gross emission reductions the models project.

Another way to observe this pattern is to consider the line segment connecting the blue marker with the red marker corresponding to a single model. Each line segment is fairly steep–the vertical difference in its endpoints is larger than the horizontal difference. When CO_2 pressure (a CO2 constraint or fee) is applied (in the Net-Zero scenario), the decrease in the CO_2 intensity of electricity production that the model projects (relative to the Reference scenario) is greater than the decrease in overall emissions (relative to the Reference scenario). These model results project that decarbonization of electricity production occurs disproportionately faster than decarbonization of the overall economy.

3.2. The role of electricity in U.S. decarbonization

Fig. 3 illustrates final energy consumption by fuel type, including electricity, in 2020, 2040, and 2050 in the Net-Zero scenario (top row) and the difference between the Net-Zero and Reference scenarios (bottom row).

Noteworthy commonalities include an increasing degree of electrification over time (the blue portions of bars) in the Net-Zero scenario (upper row). –This increase is larger in the Net-Zero scenario than in the Reference scenario (blue portions are positive and increasing over time in the lower row). In the Reference scenario, models project electricity's share of final energy would increase to 20–56 % in 2050 compared with 18–25 % in 2020; in the Net-Zero scenario, the share ranges from 17 % to 63 %. No models project that the amount of electricity consumed in 2050 in the Net-Zero scenario is less than in the Reference scenario. There seems to be agreement among these modeling teams and models that the role of electricity should be expected to increase–and increase more in a net-zero economy.

Important differences across the model results include the total energy consumed over time, which is also impacted by the degree of electrification, since electric end-uses are significantly more energy efficient. For example, an electric vehicle consumes about half as much energy than a conventional internal combustion engine vehicle [4]. While several models project increasing total energy consumption in the Net-Zero scenario, most models project decreasing total energy consumption. The contrast between, for example, ADAGE and FECM-NEMS (increasing) and EPS, US-REGEN, and USREP-ReEDS (decreasing) is

[3] Earlier model intercomparisons indicate that technology deployment is driven by a range of input assumptions and model structure and that, even when models align cost assumptions, different structural uncertainties and non-cost parameters lead to significant differences in technology shares [22,23].

Fig. 1. Total CO_2 emissions across scenarios and models. Panels show emissions from all energy uses after accounting for negative emissions ("Net Energy"), emissions from all energy-use and industrial activities ("Gross Energy"), and gross emissions from electricity production ("Electricity"). Variation in 2020 emissions reflects differences in model calibration, scope, and structure. This figure includes data from 15 models reporting all emissions components.

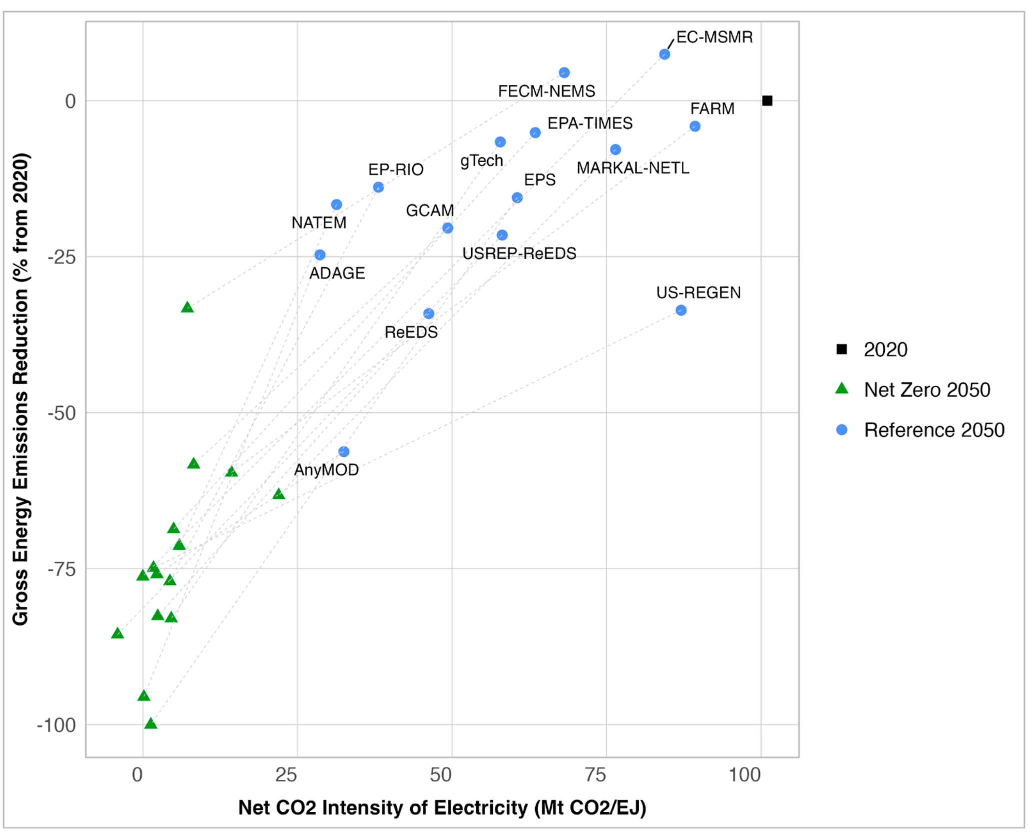

Fig. 2. Net CO_2 intensity of the electric sector compared to economy-wide emissions reductions. The vertical axis reflects reductions in total energy-related and industrial emissions, excluding negative emissions offsets ("Gross Energy"). Results are shown for the 12 models that provided these data. 2020 value from EIA, Electric Power Monthly.

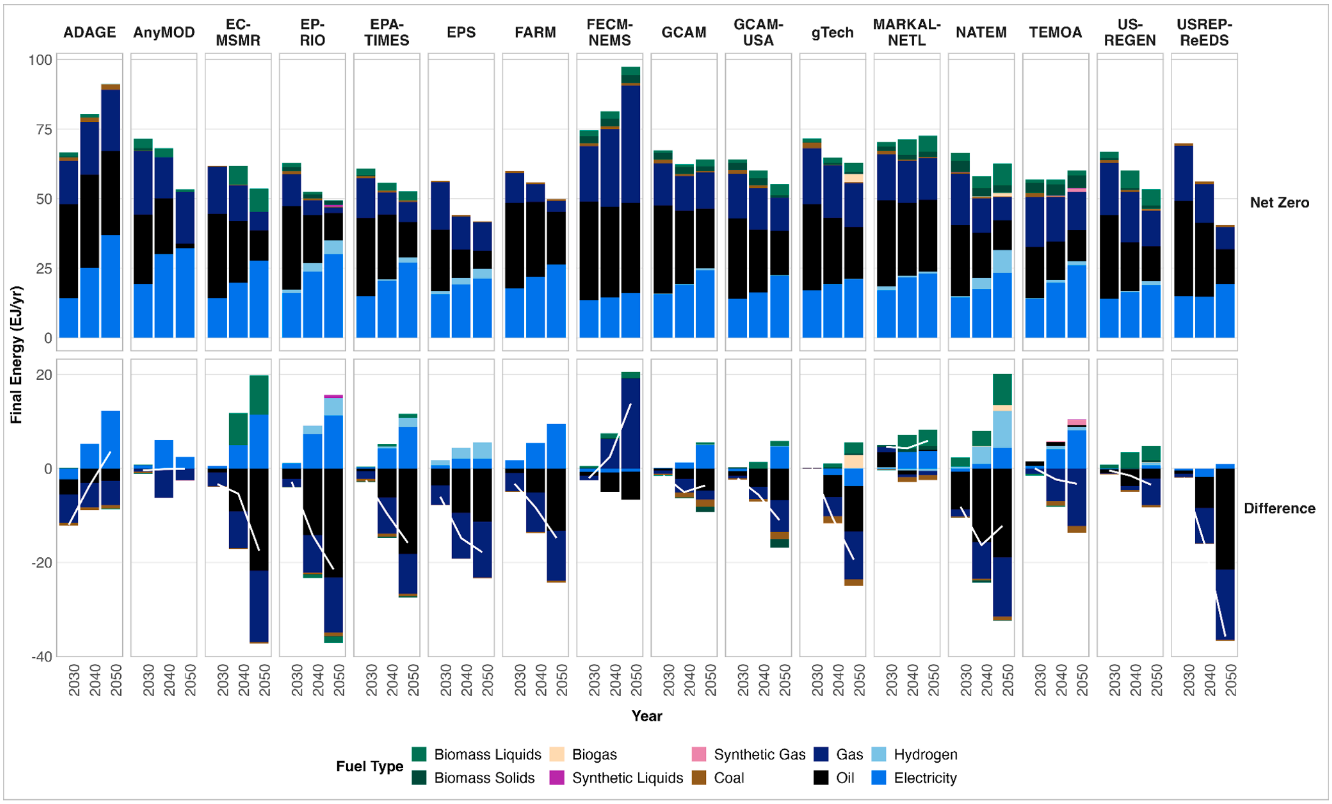

Fig. 3. Final energy by fuel over time across models. The top panel shows results for the Net-Zero scenario; the bottom panel shows the difference between the Reference and Net-Zero scenarios. The black line on the bottom panel indicates the net difference between the Reference and Net-Zero scenarios, aggregating over fuel types. The numbers atop each bar in the top panel indicate electricity's share (%) of final energy. Final energy refers to delivered energy consumed at the end-use. Results are shown for 2030, 2040, and 2050. Results are shown for the 15 models that provided these data.

especially stark and aligned with the models' projections for end-use electrification. This is an example of a key uncertainty that likely deserves additional research.

While all models consistently show an increase in electricity use, especially under the Net-Zero scenario, the extent and sectoral distribution of electrification varies significantly across models (Fig. 4).[4] Detailed EMF-37 results for end-use sectors–buildings, industry, and transportation–are discussed by Harris et al. (forthcoming) [11], Boyd et al. (forthcoming) [12], and Hoehne et al. (forthcoming) [13], respectively.

In the Net-Zero scenario, all models consistently project growth in electricity demand (see Fig. 4). However, the increase in electricity demand varies significantly among the models, ranging from as low as 24 % in FECM-NEMS to as high as 176 % in ADAGE. Note that many of these models do not incorporate recent projections for data center load growth [14].

A common driver behind the increase in electricity demand is the electrification of the transportation sector, accounting for 3 % to 33 % of the growth across models. Additionally, there are notable increases in electricity demand in the industry sector, accounting for −3.5 % to 45 % of the growth across models, and buildings, accounting for −4 % to 32 % of the growth across models. For buildings and industry, US-REGEN and USREP-ReEDS are exceptions as they show a reduction or very limited growth in electricity demand. For these two models, the building sector results reflect differing combinations of increased energy efficiency through traditional measures, such as improved insulation or building envelope design, and offsetting electric resistance heating with more efficient heat pumps. In the case of US-REGEN, there is a significant increase over time in the share of service demand met with electricity in buildings and industry, but because this effect is largely offset by efficiency improvements also happening over time, there is not a significant increase in electricity demand, and even a slight decrease in the total for buildings. For example, heat pumps replace electric resistance heating as well as gas furnaces, and heat pumps themselves get more efficient. Moreover, other already electrified end-uses such as lighting, appliances, and electronics are assumed to improve in efficiency faster than service demand grows, resulting in countervailing structural change to the electrification trend. For USREP-ReEDS, the reduction in electricity demand by the industrial sector in the net-zero scenario reflects limited electrification potential in this sector. This is due to two factors in USREP: (1) electrification technologies for many industrial processes are not explicitly represented; and (2) the substitution possibility between electricity and fossil fuels remains constant over time. Therefore, as fossil fuels become increasingly costly under the net-zero policy, the industrial sector, without the ability to easily switch to relatively cheaper electricity or adopt new electric technologies, has to reduce production to meet emissions targets, which in turn reduces its demand for electricity. For EC-MSMR, the lack of growth for electricity demand in the transportation sector can mainly be attributed to the fact that the model relies on cost minimization and substitution elasticities for fuel switching between conventional energy types (coal, oil, gas, electricity). Even with increased elasticities, substitution toward electricity is generally a slower and more gradual process. Renewable fuels also act as perfect substitutes for fossil fuels making them an attractive fuel switching option that can replace larger amounts of fossil energy more quickly instead of the gradual substitution towards electricity via elasticities. These assumptions represent a conservative view of the sector's future electrification potential, leading to outcomes different from other

[4] Note that 2020 electricity use varies quite significantly across models, indicating different *calibration, scope, and structure across models.*

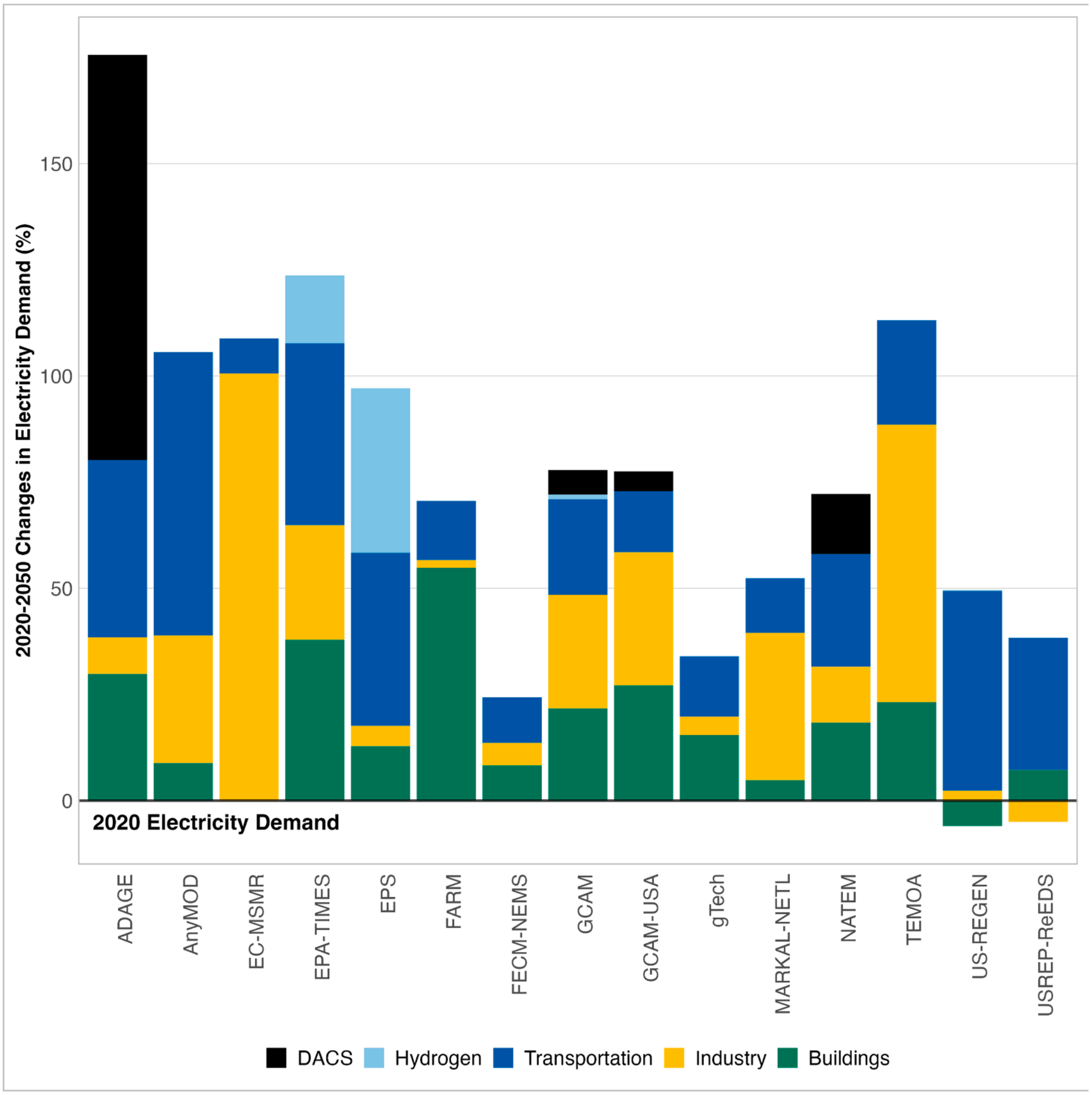

Fig. 4. Growth in Electricity Demand by Sector from 2020 to 2050 under Net Zero Scenarios as a Fraction of Total 2020 Electricity Demand.

models which may have more optimistic options for the sector.

Furthermore, EC-MSMR, TEMOA, Markal-NETL, and GCAM project significant increase in electricity demand for industrial electrification. The high growth in electricity consumption for industry and hydrogen for EC-MSMR reflects the view that renewable fuels are easier direct substitutes of fossil fuels.

DACS is projected to account for 0 to 30 % of the demand increase across the models. DACS acts as a backstop technology, i.e., it is used to offset emissions from harder (more costly) to abate activities. Its deployment is directly related to the technology assumptions within the models and the carbon price trajectories of the respective scenarios. A noteworthy difference is ADAGE, projecting a significant growth in electricity demand for DACS, reaching 12 EJ in 2050, mostly because of a relatively lower break-even cost assumption for DACS. The way that DACS is powered differs across these models–and in some models it is directly associated with electricity while in others it is not, making the results in this figure not directly comparable. BECCS is another technology that can be used to offset emissions; Sands et al. (forthcoming) [15] detail the role of BECCS in EMF-37 results.

Fig. 5 shows the degree of electrification within each sector (measured as the share of sectoral final energy demand coming from electricity) and the share of total electricity demand consumed by each sector, illustrating both the role of electricity in decarbonizing different sectors as well as the importance of various sectors in determining future electricity demand.

In 2020, buildings accounted for approximately 75 % of total electricity demand, making them the largest electricity consuming sector. About half of the final energy consumed in the building sector came from electricity. By 2050 in the Net-Zero scenario, electrification of buildings is projected to grow to 55–100 %: multiple models, including AnyMOD, EPA-TIMES, EPS, and USREP-ReEDS, suggest that building electrification would surpass 90 %. On the contrary, models such as US-REGEN, FECM-NEMS, and MARKAL-NETL project a lower level of electrification, less than 60 %. But the absolute growth in electricity use in buildings is overshadowed by the faster-growing electricity demand in other sectors, resulting in its reduced share of total electricity consumption.

Currently, electricity constitutes less than 20 % of the industry sector's energy consumption. Industry electrification is projected to increase in the Net-Zero scenario, but electricity's share of industrial final energy demand remains below about 40 % across all models. Although there would be an increase in the overall electricity usage in the industrial sector over time, the proportion of total electricity consumed by

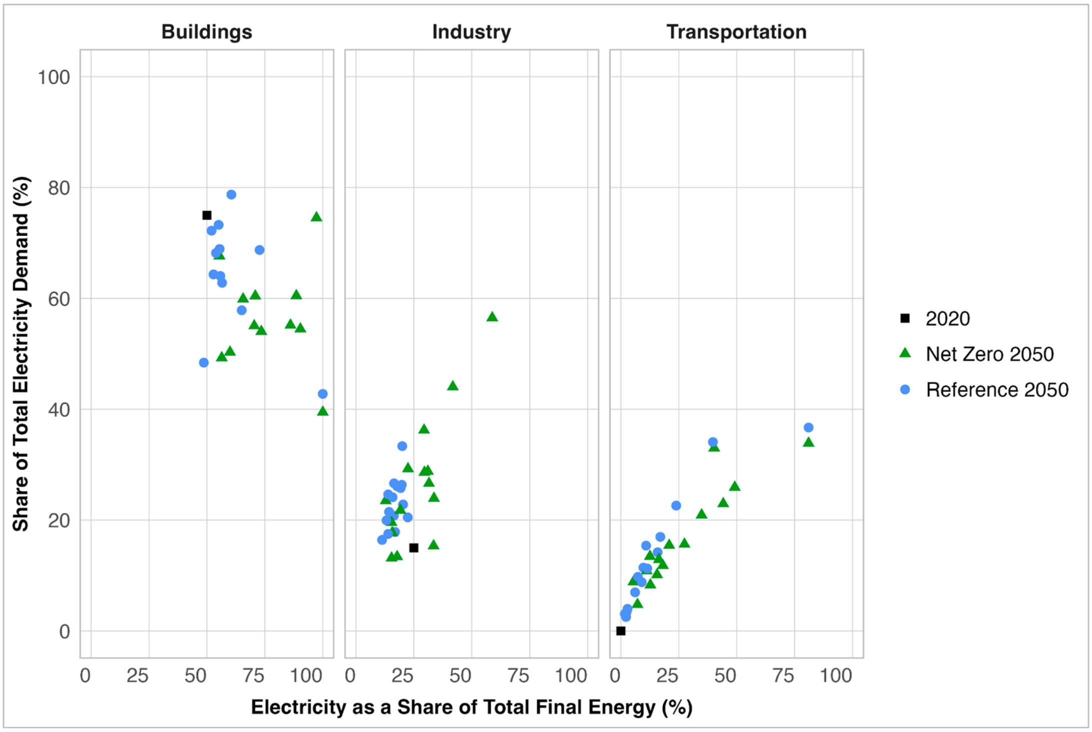

Fig. 5. Share of sectoral final energy demand from electricity and share of total electricity consumed by each sector. It should be noted that passenger vehicle electrification is put under "buildings" rather than transportation.

the industry is not expected to undergo substantial changes.

Today less than 1 % of transportation's final energy comes from electricity.[5] In the Net-Zero scenario, most models project an increase in transportation electrification. AnyMOD projects that up to 80 % of transportation's final energy consumption would be supplied by electricity, while several other models project about 40 % transportation electrification, and others show less than 20 %. Consequently, the share of total electricity used in transportation is projected to rise from less than 1 % in 2020 to a range of 15–35 % by 2050, putting it on approximately equal footing with the other end-use sectors as a share of electricity demand in 2050.

The above discussion focuses on electricity's share of final energy, which measures direct electricity use but does not consider indirect uses of electricity, such as for hydrogen production. Hydrogen has traditionally been used as a critical feedstock in the chemical industry and refineries, and its production is historically based almost exclusively on fossil fuels and associated GHG emissions. However, hydrogen produced through electrolysis has increasingly gained traction as a promising contributor to decarbonization (if electricity is sourced from low-emissions technologies) due to hydrogen's potential capability as an energy storage medium. Indeed, absent offsets, low-carbon electrolyzed hydrogen may be vital for industrial decarbonization and many models project a large role for electrolytic hydrogen in a Net-Zero future. Fig. 6 shows hydrogen production by source across models in the Net Zero scenarios. Further detail about hydrogen modeling is provided by Melaina et al. [16].

It should be noted that MARKAL-NETL and EPS include 8–13 MMT of current or conventional hydrogen use in 2020 in petroleum refining, production of ammonia, and production of other chemical products. Other models only estimate new hydrogen demand. Additionally, AnyMOD has only modeled hydrogen for light-duty vehicles.

In the Reference scenario, among models that report hydrogen results, hydrogen production (and corresponding demand) remains limited through 2050 and continues to be based on fossil fuels. However, some models (EC-MSMR, EPS, NATEM, TEMOA) estimate significant growth in hydrogen production in the Net-Zero scenario with annual production exceeding 4 EJ/yr. Other models (EPA-TIMES, US-REGEN, GCAM) project lower quantities of hydrogen production (~<2 EJ/yr), while others show no growth in hydrogen. Furthermore, even among those that show growth in hydrogen production, significantly divergent views on the source of hydrogen production in the Net-Zero by 2050 scenario. Noticeably, while EC-MSMR, EPS, and EPA-TIMES show hydrogen production predominantly from electrolysis, TEMOA and US-REGEN use biomass (with CCS), whereas MARKAL-TIMES and NATEM show a heavy reliance on hydrogen from natural gas (with and without CCS, respectively). These diverse results on the amount and source of hydrogen production highlight tremendous uncertainty in future hydrogen demand and production [16].

Fig. 7 illustrates the relationship in the model projections between electricity's share of final energy consumption (horizontal axis) and energy consumption per capita (vertical axis). A clear theme in these results is that decarbonization is consistent with an increase in electricity's share in final energy.[6] Nearly all models show an increased role of electricity in the Net-Zero scenario compared to the Reference scenario (the red markers are to the right of the blue markers). Most models show decreased final energy per capita in the Net-Zero scenario relative to the Reference scenario. These lower final energy projections reflect electrification trends, where electric end-use technologies typically have much lower final energy per unit of service demand relative to other fuels. For example, replacing 3 kWh of gas heating with 1 kWh of electricity via a heat pump would both reduce final energy consumption per capita and increase the electricity share of final energy. The

[5] Markal-NETL and AnyMOD report slightly higher shares for 2020.

[6] The exception to this pattern is the FECM-NEMS model. In this model, most sectors have reduced consumption of electricity in the Net-Zero scenario due to price-induced energy efficiency offsetting electrification, while transportation has increased electricity from electric vehicles. Also, hydrogen production is not represented in this version of FECM-NEMS.

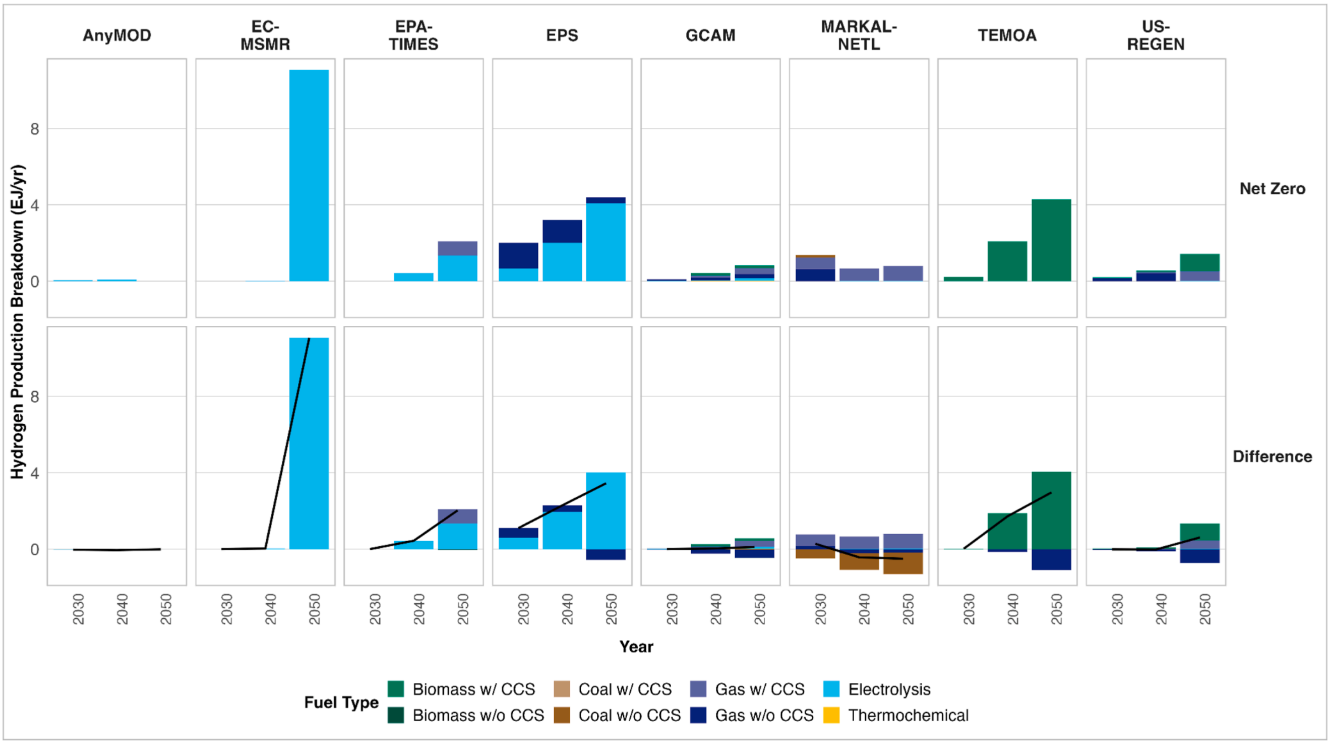

Fig. 6. Hydrogen Production by Source. The top panel shows results for the Net-Zero scenario; the bottom panel shows the difference between the Reference and Net-Zero scenarios. The black line on the bottom panel indicates the net difference between the Reference and Net-Zero scenarios, aggregating over all production sources.

reduction in final energy per capita can also reflect the increased adoption of traditional energy efficiency measures. Models have different degrees of detail in terms of energy efficiency pathways represented Browning, et al. [3]. One caveat is that annual electricity demand does not indicate how peak demand, load profiles, and flexible demand may change. Further study and additional resolution in many of the models are needed to analyze these effects further. As but one example, FECM-NEMS displays lower electricity demand in the Net-Zero scenario relative to the Reference scenario due to lower end-use electrification than in many other models, and the primary DAC technology uses natural gas (with CCS) rather than electricity for its energy source. This lower electrification is due to several factors – few electric technology options in the industrial sector, relatively conservative electric vehicle assumptions, and assumptions about consumer behavior that inhibits rapid change in fuel choices in buildings and transportation. At the same time, higher electricity prices lead to reduced electricity demand in some energy services (such as space heating) relative to the Reference scenario. This trend in the FECM-NEMS projections occurs while total energy demand in the Net-Zero scenario rises in large part due to energy (natural gas) consumption for DAC, a more dominant contributor to achieving the Net-Zero goals than in most other models.

3.3. Electricity supply

Fig. 8 illustrates annual electricity generation by energy source projected by each model for the U.S. in 2030, 2040, and 2050 in the Net-Zero scenario (top row) and the difference between the Net-Zero and Reference scenarios (bottom row) for the 13 models presenting these data. Fig. 9 shows the corresponding capacity projections.

In the Net-Zero scenario (top row, Fig. 8), while there are many common themes, these models generally show a diversity of pathways and endpoints for the electricity sector in achieving economy-wide Net-Zero GHG emissions. The models consistently find growth in renewable electricity, particularly from wind and solar technologies. This growth is driven by a combination of demand growth (see Section 3.2) and the net-zero emissions target. Most models estimate a mix of new wind and solar generation, with slightly higher wind generation. The exception is EC-MSMR, where incremental growth in low-emissions generation comes almost entirely from solar generation. Growth in generation from non-renewable technologies is significantly more limited or even declining. Coal without CCS is rapidly eliminated in all but one model, and the use of natural gas declines over time in most models; coal and gas with CCS each play a role in some models. Geothermal power does not play a large role in any of the models, making up about 0.4 % of U.S. production. Projections for biopower are varied between the models, with the greatest growth found by AnyMOD, EPA-TIMES, GCAM, FARM, and MARKAL-NETL. The other models find very limited growth in biopower, thus highlighting the allocation of biomass across sectors as a key uncertainty.

The bottom row of Fig. 8 shows the difference in electricity generation projections between the Reference and Net-Zero scenarios, with the line indicating the net total change. All models project increased electricity production by 2050 in the Net-Zero scenario relative to the Reference scenario. All models project less electricity production using coal and gas without CCS and more solar and wind in the Net-Zero scenario relative to Reference. A few models (including ADAGE, MARKAL-NETL and US-REGEN) have increased nuclear generation relative to Reference. And a few models (including EPA-TIMES and MARKAL-NETL) project increased coal with CCS in the Net-Zero scenario relative to the Reference scenario. And a few models (including FARM, GCAM and MARKAL-NETL) project a larger role for biomass in the Net-Zero scenario relative to Reference. Natural gas is also reduced by 50–100 % below the Reference scenario. Other than ADAGE's projections, hydropower projections are similar between the Reference and Net-Zero scenarios across the models.

Capacity results, shown in Fig. 9, follow similar trends as the generation ones. However, the differences in electricity capacity between the Reference and Net-Zero scenarios are less pronounced than the

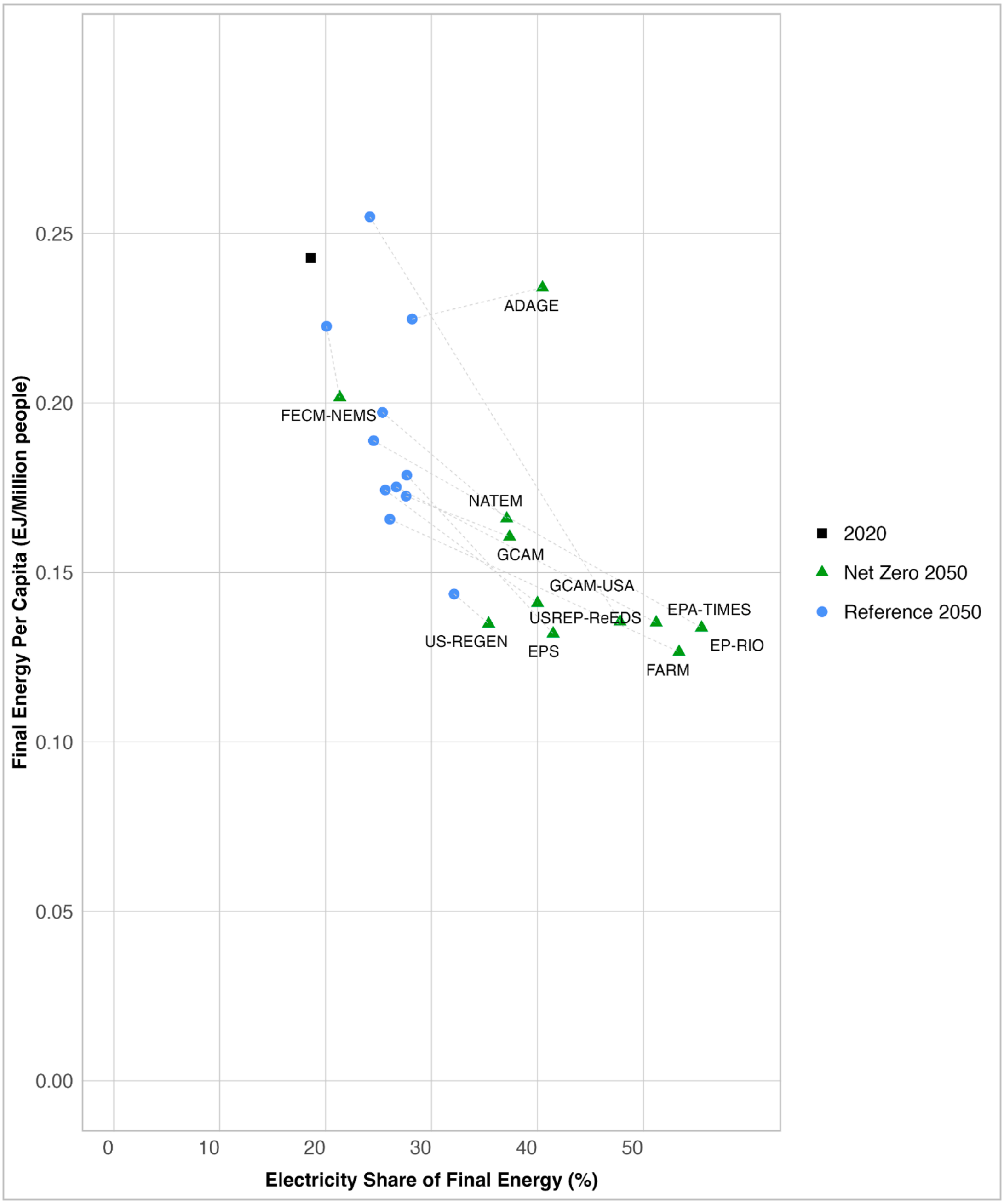

Fig. 7. Electricity Share in Final Energy v. Final Energy per Capita. The graph maps final energy per capita against electricity share of final energy for the base year (2020), results for 2050 in the Reference Scenario and in the Net-Zero scenario.

differences for annual electricity generation (Fig. 8) in large part because large amounts of gas capacity remain or even grow under the Net-Zero scenario. Most Net-Zero scenarios have more than twice as much wind and solar capacity as the Reference scenario in 2050 but only display a smaller gas capacity by less than a third.[7] This gas capacity provides important grid reliability services even as gas generation declines.

The projected growth in renewable electricity under the Net-Zero scenario suggests significant increases in the variability of electricity supply under decarbonization futures. Fig. 10 shows the combined share of wind and solar generation in total annual generation. Compared to the Reference Scenario, (almost) all models project a significantly higher estimated electricity share from variable renewable energy sources (VREs) under the Net-Zero scenario. Further, over half of the models project greater than 50% estimated electricity share from variable renewable energy sources (VREs) by 2050, far exceeding the 15 % VRE share in the United States in 2022. Note that under both Reference and Net-Zero scenarios, there is a wide range of 2050 VRE shares between models (20 % to 75 % in Reference and 45 % to 90 % in Net-Zero), pointing to disparate expectations for wind and solar cost reductions and/or the ability to economically integrate these variable sources.

Assessing the shift from a power system dominated by fossil-fueled resources to one dominated by wind and solar energy requires

[7] While we do not study the capacity factors (CFs) of various technologies in this paper, the difference in operating modes of gas-fired generation between Reference and Net-Zero scenarios could lead to different CFs for gas in these scenarios. It is likely that the CFs for solar and wind could also be a significant factor influencing the differences between capacity and generation.

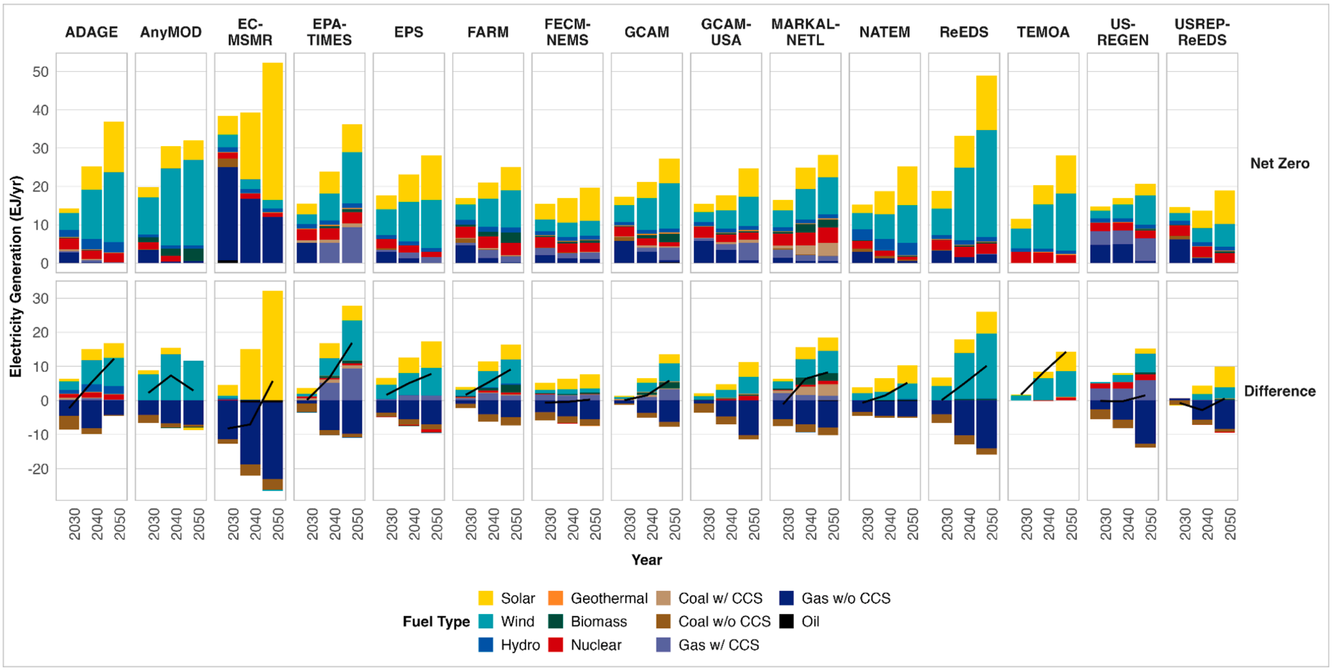

Fig. 8. Electricity Generation by source. The top panel shows results for the Net-Zero scenario; the bottom panel shows the difference between the Reference and Net-Zero scenarios. The black line on the bottom panel indicates the net difference between the Reference and Net-Zero scenarios, aggregating over fuel types.

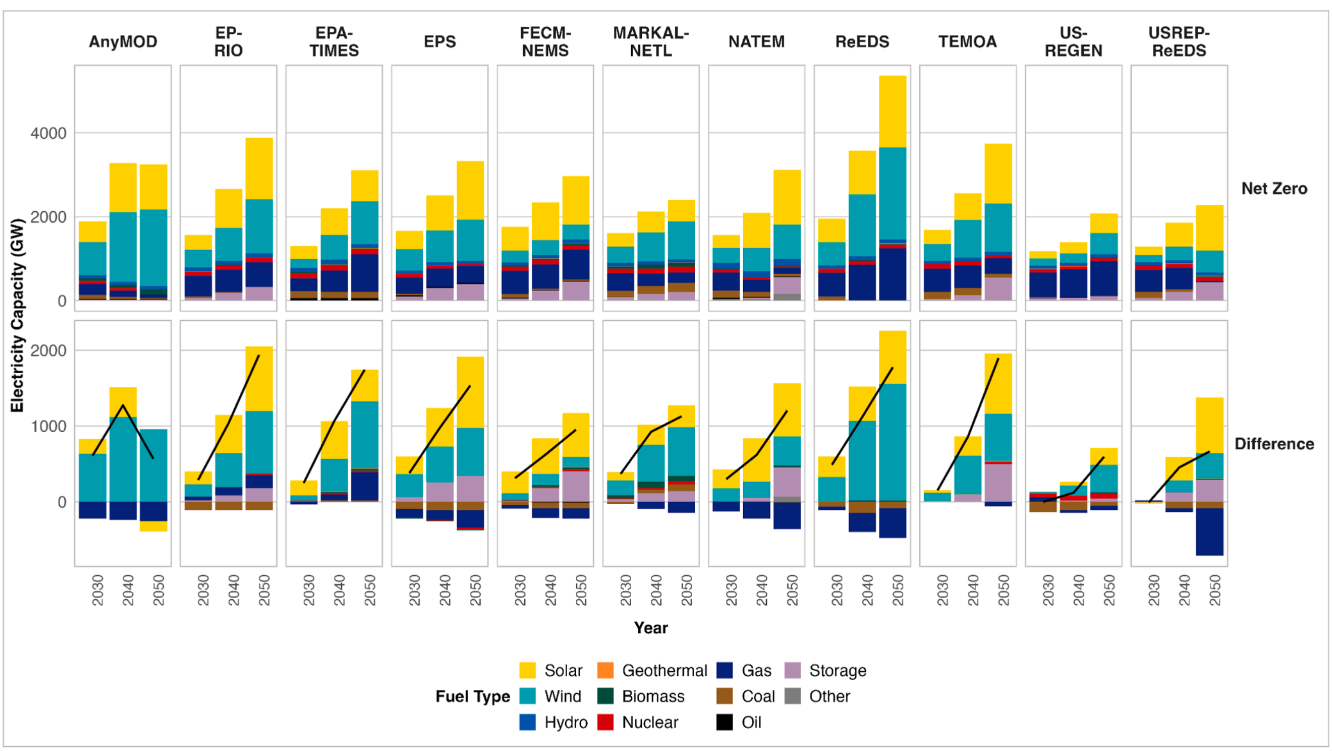

Fig. 9. Electricity Capacity by source. The top panel shows results for the Net-Zero scenario; the bottom panel shows the difference between the Reference and Net-Zero scenarios. The black line on the bottom panel indicates the net difference between the Reference and Net-Zero scenarios, aggregating over fuel types.

attention to their unique characteristics [17]. Since these technologies are weather-dependent, electricity generation from wind and solar is inherently variable over multiple timescales and can be difficult to forecast, especially at longer timescales. In addition, their location dependence introduces siting considerations and greater needs for electricity transmission to deliver electricity produced from VREs to demand. These characteristics, along with the inverter-based nature of wind, solar PV, and batteries, create challenges to achieving very high shares of VREs while maintaining the high reliability standards expected in the United States [16]. At the same time, end-use electrification offers increased opportunities to provide demand-flexibility, like managed EV charging, that can support power system planning and operations [18]. Fully assessing these complex interactions is outside the scope of the EMF-37.

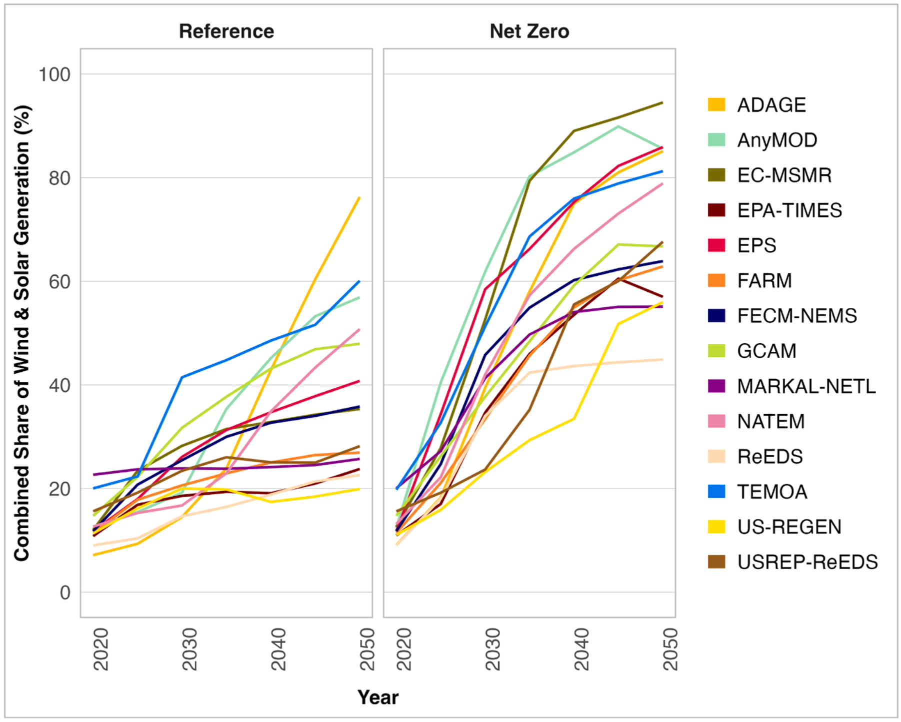

Fig. 10. Combined Share of Wind & Solar Generation Over Time. The left panel shows the trajectory of combined share of wind and solar generation as a percentage of total electricity generation over time in the Reference scenario. The right panel shows the results for the Net-Zero scenario.

Transitioning the U.S. energy system to a net-zero grid requires not only a significant increase in renewable energy generation capacity, as seen in prior sections of this paper, but also the integration and widespread adoption and expansion of new transmission and storage technologies and distributed energy resources. The roles of transmission [19] storage, and dynamic supply-demand integration in this transition are crucial as they are key enablers of the efficient distribution of renewable energy across the grid and the reliable supply of electricity.

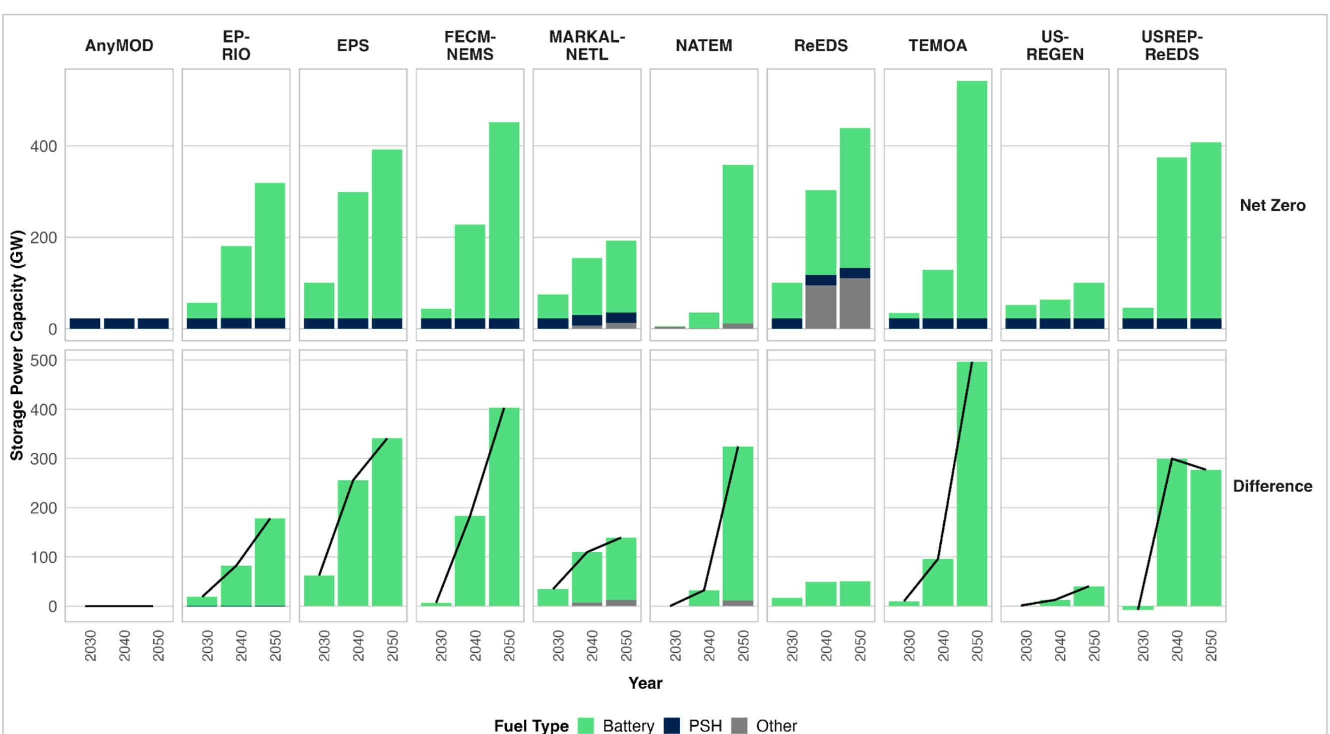

Fig. 11. Storage Power Capacity by Form of Storage. The top panel shows the evolution of total storage power capacity over time in the Net-Zero scenario. The bottom panel shows the difference between the Reference and Net-Zero scenarios. The black line on the bottom panel presents the net difference between the two scenarios across storage types. Results are shown for battery, pumped hydrogen storage (PSH), and others.

Grid-scale storage plays an important role in the Net-Zero Scenario by providing important system services that range from short-term balancing and operating reserves to long-term energy storage. Figs. 11 and 12 show the storage deployment results from the Reference and Net-Zero scenarios from the models that model grid-scale storage. In both scenarios, growth in energy storage is often found in both scenarios and is primarily in the form of batteries. However, note that the magnitude of storage deployment is estimated to be significantly greater under the Net-Zero scenario in most models. FECM-NEMS, EPS, EP-RIO, NATEM, and TEMOA all find greater than 300 GW of energy storage by 2050 in this case. The limited reporting of energy storage results, along with a limited representation of transmission, demand flexibility, and other grid flexibility measures indicate the need for further model development in many participating models or supplementing the scenario analysis here with additional higher-fidelity modeling [20,21].

4. Conclusion

The modeling results discussed in this paper show how different models project different evolutions of the electricity sector in scenarios achieving net-zero GHG emissions in the U.S. by 2050. There are many different views of how net-zero emissions can be achieved, based on different views of the relative cost and performance of technologies, different views of which technologies may be available and the roles they may play, and different views of how feedback occurs across the U. S. economy. While there are many common themes–including the concept that electricity will play a large and leading role in overall U.S. decarbonization and that electrification will contribute to the decarbonization of other sectors–there are also many differences in perspectives and disagreement on solutions.

- **Pace of decarbonization.** In Net-Zero scenario projections, CO_2 emission reductions generally occur more rapidly in electricity production than in the overall U.S. economy. This is generally due to there being more cost-effective options for electricity decarbonization that have been deployed at scale for over a decade–and electrification being a cost-effective strategy for other sectors as electricity decarbonizes. Amongst the models studied, there is consensus on electricity sector decarbonizing the fastest and disagreement on the level of gross emissions reductions and the extent to which CDR is utilized as a means of getting to net zero.
- **End-Use Electrification.** For many end-uses currently using fossil fuels (e.g., petroleum in transportation, natural gas in space and water heating, and many others), electrification is a cost-effective way to increase energy efficiency and decarbonize. Electricity's share of final energy in 2050 ranges from 17 % to 63 % across the models under the Net-Zero scenario, compared to 18–25 % in 2020. There is, however, significant variety across models and the degree to which various sectors electrify remains an area of disagreement. Amongst the models studied, there is consensus that electricity demand grows, primarily driven by transportation electrification under net zero. There are major differences in the extent of growth projected, in large part due to differences in projections of the extent to which CDR is utilized (In the presence of significant uptake of CDR, the degree of electrification required is reduced.)
- **Electricity production.** Across all models, the role of solar, wind, and storage in electricity production increases significantly, even in the Reference Scenario and to a much greater extent in the Net-Zero scenario. However, the electricity generation mix differs significantly across models. In particular, some models project an increased role for natural gas in electricity production, at least in the presence of carbon capture in one form or another.

CRediT authorship contribution statement

Ruying Gao: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Trieu Mai:** Writing – original draft, Conceptualization. **Seyed Shahabeddin Mousavi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Charles Rossmann:** Writing – review & editing, Writing – original draft, Conceptualization. **Matthew Binsted:** Writing – original draft, Methodology. **John**

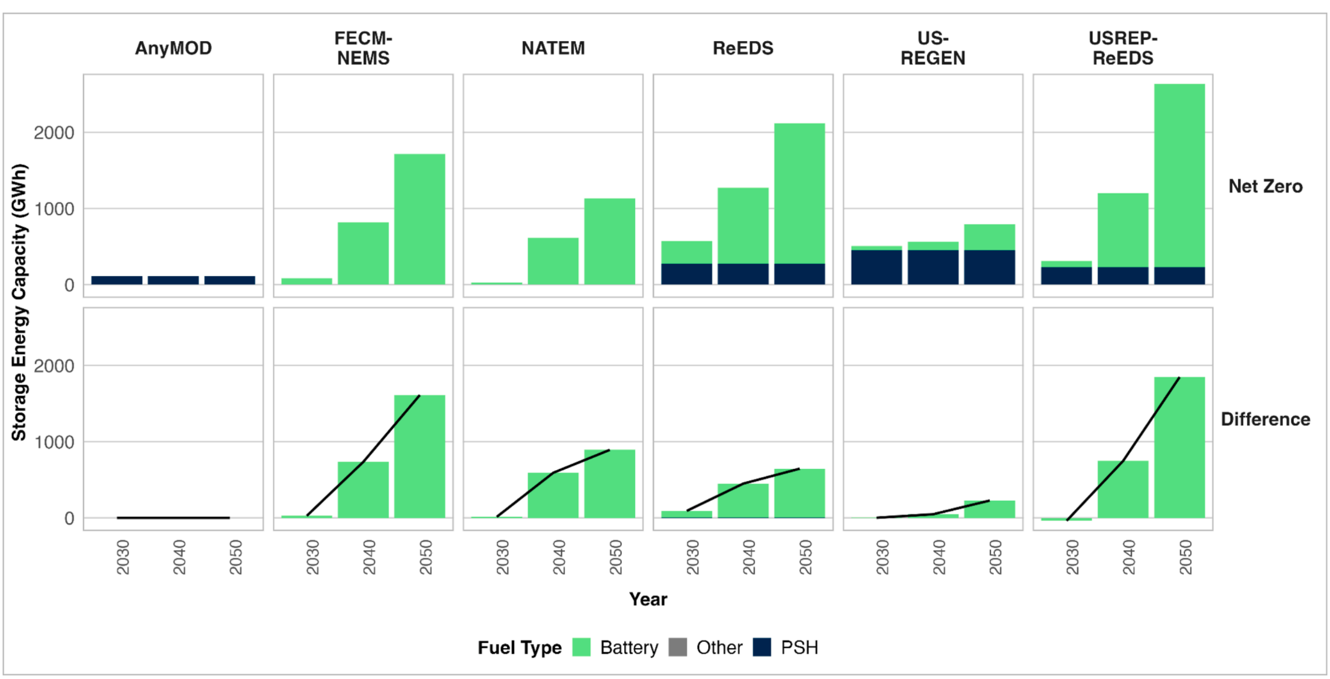

Fig. 12. Storage Energy Capacity by Form of Storage. The top panel shows the evolution of total storage energy capacity over time in the Net-Zero scenario. The bottom panel shows the difference between the Reference and Net-Zero scenarios. The black line on the bottom panel presents the net difference between the two scenarios across storage types. Results are shown for battery and pumped hydrogen storage (PSH).

Bistline: Writing – original draft, Methodology, Conceptualization. **Geoff Blanford:** Writing – original draft, Methodology, Conceptualization. **Morgan Browning:** Writing – review & editing, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Matthias Fripp:** Writing – original draft, Validation, Project administration, Conceptualization. **Patrick Lamers:** Writing – original draft, Investigation. **Matteo Muratori:** Writing – original draft, Validation. **Sharon Showalter:** Data curation. **John Weyant:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The views expressed in the article do not necessarily represent the views of the United States Environmental Protection Agency (U.S. EPA), the United States Department of Energy (U.S. DOE), the U.S. Government, or Electric Power Research Institute (EPRI). The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. The contributions of the Stanford University affiliated authors of this paper were supported by the United States Department of Energy (U.S. DOE) through grant EI0003267 and the United States Environmental Protection Agency (U.S. EPA) through grant 83998801. Some authors of this paper are affiliated with the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U. S. Department of Energy (DOE) under Contract No. DE-AC36–08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Strategic Analysis Office. Patrick Lamers received funding from EPA OTAQ under IAG 19–16388. Shahab Mousavi & Ruying Gao received funding through Stanford University.

The authors would like to acknowledge the contributions of the EMF-37 modeling teams, participants in several scoping workshops, and Daniel Huppmann and others at IIASA for use of—and help with—data submissions.

References

[1] United States Department of State and the United States Executive Office of the President, The Long-term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050, 2021.
[2] FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies, The White House, 2021. www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/. Press release.
[3] M. Browning, J. McFarland, J. Bistline, et al., Net-Zero CO_2 by 2050 scenarios for the United States in the energy modeling forum 37 study, Energy Clim. Change 4 (2023) 100104, https://doi.org/10.1016/j.egycc.2023.100104.
[4] M. Muratori, M. Alexander, D. Arent, et al., The rise of electric vehicles—2020 status and future expectations, Progress Energy 3 (2) (2021) 022002.
[5] EIA, Annual Energy Outlook 2023, 2023. https://www.eia.gov/outlooks/aeo/.
[6] J. Bistline, et al., Emissions and energy impacts of the inflation reduction act, Science 380 (2023) 1324–1327, https://doi.org/10.1126/science.adg3781.
[7] J.E.T Bistline, M. Brown, M. Domeshek, C. Marcy, N. Roy, G. Blanford, D. Burtraw, et al., Power sector impacts of the Inflation Reduction Act of 2022, Environ. Res. Lett. 19 (1) (2023) 014013.
[8] ... & J.E. Bistline, M. Brown, M. Domeshek, C. Marcy, N. Roy, G. Blanford, A. Zhao, Power sector impacts of the inflation reduction act of 2022, Environ. Res. Lett. 19 (1) (2023) 014013, https://iopscience.iop.org/article/10.1088/1748-9326/ad0d3b/meta.
[9] J.E.T Bistline, G. Blanford, B. Gale, M. Browning, Y. Cai, J. Edmonds, et al., Policy Implications of Net-Zero Emissions: A Multi-Model Analysis of United States Emissions and Energy System Impacts, Energy Clim. Change (2025) 100191.
[10] M. Binstead, E. Lochner, J. Edmonds, et al., Carbon management technology pathways for reaching a U.S. economy-wide net-zero emissions goal, Energy Clim. Change 5 (2024) 100154, https://doi.org/10.1016/j.egycc.2024.100154.
[11] Harris, et al. (forthcoming). Net-Zero CO2 pathways for the United States buildings sector: findings from the energy modeling forum 37 building study group. Energy Clim. Change.
[12] Boyd, et al. (forthcoming). Is the industrial sector hard to decarbonize or hard to model? A comparison of industrial model structure and net-zero scenario results in EMF-37. Energy Clim. Change.
[13] Hoehne, et al. (forthcoming). Role of transportation in net-zero emission futures: insights from EMF-37. Energy Clim. Change.
[14] Blanford and Bistline, Powering Data Centers: U.S. Energy System and Emissions Impacts of Growing Loads, 2024. EPRI Report 3002031198.
[15] Sands, et al. (forthcoming). Bioenergy pathways within United States net-zero CO2 emissions in the Energy Modeling Forum 37 study.
[16] Melaina, M., Green, T., Lenox, C., Browning M., Bahn O. (forthcoming). Modeling hydrogen markets: energy-economic model development status and decarbonization scenario results. Energy Clim. Change.
[17] P. Denholm, D.J. Arent, S.F. Baldwin, et al., The challenges of achieving a 100% renewable electricity system in the United States, Joule 5 (6) (2021) 1331–1352.
[18] M.B. Anwar, et al., Assessing the value of electric vehicle managed charging: a review of methodologies and results, Energy Environ. Sci. (2022). https://pubs.rsc.org/en/content/articlelanding/2022/ee/d1ee02206g.
[19] P.R. Brown, A. Botterud, The value of inter-regional coordination and transmission in decarbonizing the U.S. electricity system, Joule 5 (1) (2021) 115–134.
[20] J. Bistline, G. Blanford, T. Mai, J. Merrick, Modeling variable renewable energy and storage in the power sector, Energy Policy 156 (2021) 112424.
[21] T. Levin, J. Bistline, R. Sioshansi, et al., Energy storage solutions to decarbonize electricity through enhanced capacity expansion modelling, Nat. Energy 8 (11) (2023) 1199–1208.
[22] T. Mai, J. Bistline, Y. Sun, W. Cole, C. Marcy, C. Namovicz, D. Young, The role of input assumptions and model structures in projections of variable renewable energy: a multi-model perspective of the US electricity system, Energy Econ. 76 (2018) 313–324. https://www.sciencedirect.com/science/article/abs/pii/S0140988318304213.
[23] ... & J. Bistline, S. Bragg-Sitton, W. Cole, B. Dixon, E. Eschmann, J. Ho, A. Sowder, Modeling nuclear energy's future role in decarbonized energy systems, IScience 26 (2) (2023), https://www.cell.com/iscience/fulltext/S2589-0042(23)00029-9.