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Net-zero CO_2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study

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A B S T R A C T

The Energy Modeling Forum (EMF) 37 study on deep decarbonization and high electrification analyzed a set of scenarios that achieve economy-wide net-zero carbon dioxide (CO_2) emissions in North America by mid-century, exploring the implications of different technology evolutions, policies, and behavioral assumptions affecting energy supply and demand. For this paper, 16 modeling teams reported resulting emissions projections, energy system evolution, and economic activity. This paper provides an overview of the study, documents the scenario design, provides a roadmap for complementary forthcoming papers from this study, and offers an initial summary and comparison of results for net-zero CO_2 by 2050 scenarios in the United States. We compare various outcomes across models and scenarios, such as emissions, energy use, fuel mix evolution, and technology adoption. Despite disparate model structure and sources for input assumptions, there is broad agreement in energy system trends across models towards deep decarbonization of the electricity sector coupled with increased end-use electrification of buildings, transportation, and to a lesser extent industry. All models deploy negative emissions technologies (e.g., direct air capture and bioenergy with carbon capture and storage) in addition to land sinks to achieve net-zero CO_2 emissions. Important differences emerged in the results, showing divergent pathways among end-use sectors with deep electrification and grid decarbonization as necessary but not sufficient conditions to achieve net zero. These differences will be explored in the papers complementing this study to inform efforts to reach net-zero emissions and future research needs.

1. Introduction

1.1. Energy modeling forum (EMF)

The Stanford Energy Modeling Forum (EMF) was established in 1976 to convene international working groups of modelers and model users in energy, economics, and the environment to explore specific topics, identify important issues, and publicly share insights. EMF leverages analysis to identify relevant insights that are robust across a wide range of models and future scenarios to inform policy and private decisions, provide explanations for differences in results from different models where possible, and identify high priority areas for future research and model development. The EMF 37 study on deep decarbonization and high electrification continues a long tradition of EMF studies since the mid-1990s that have explored climate policy issues, focusing on achieving economy-wide net-zero carbon dioxide (CO_2) emissions by mid-century in North America.

This paper comprises 16 models running a common set of deep decarbonization and high electrification scenarios that explore how environmental, energy system, and economic outcomes depend on decarbonization goals, sectoral guideposts and policies, and technological advancement. A key objective of this model intercomparison project

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is to understand which insights are robust across models and scenarios and which are more sensitive to model-specific assumptions. This paper delves not only into economy-wide insights and transitions, but within and across energy supply and demand sectors and CO_2 removal options.

1.2. Scope of the overview paper

The objectives of this paper are to: (1) provide the motivation for the EMF 37 study, (2) show high-level economy-wide results for two net-zero CO_2 emissions scenarios by 2050 for the United States, and (3) present the roadmap of forthcoming complementary EMF 37 analyses.

1.3. Motivation for the study

Significant greenhouse gas (GHG) emissions reductions are needed to mitigate severe impacts of ongoing climate change [1]. The EMF 37 study explores decarbonization and electrification pathways for the three largest economies of North America: the United States, Canada, and Mexico. The three economies are tightly linked by trade and have made emission reduction pledges under the Paris Agreement. Importantly, both the United States[1] [2,3] and Canada [4] have set goals of net-zero economy-wide GHG reductions by 2050 as outlined in their Long Term Strategies. This study provides a comprehensive and timely analysis of pathways toward achieving net-zero CO_2 and GHG emissions.

The rationale for the EMF 37 study was to understand the role for electrification under economy-wide decarbonization pathways in important economic sectors—transportation, buildings, and industry. Much of the deep decarbonization literature points to the decarbonization of the power sector and the electrification of many end-uses. However, there is a lack of consensus on the ultimate potential and extent of electrification, the rate at which it can be implemented given technical, behavioral, economic, and deployment limits (e.g., infrastructure, workforce, supply chains, manufacturing), and competition from other carbon mitigation and management options such as land sinks, carbon capture and storage, direct air capture, and the use of clean hydrogen and other sustainable fuels.

Major motivating questions for EMF 37 include: What demand-side transformations are needed to reach economy-wide net-zero emissions goals? To what extent can the transportation, buildings, and industrial sectors be electrified to achieve deep decarbonization and net-zero emissions? How can the electricity sector transform to achieve net-zero emissions? How might technological and behavioral change alter the extent of electrification? What are the implications of deep decarbonization scenarios on the energy system and economic and environmental outcomes in North America?

Since the inception of the EMF 37 study in October 2020 and launch in October 2021, net-zero emissions targets have gained significant policy relevance, and the scope of this study has evolved to improve the modeling community's ability to analyze net-zero pathways. Importantly, the study is designed to engage multiple types of energy and economy-wide models as well as sectoral and technology experts focused on transportation, industry, buildings, and carbon management.

This study builds on a growing number of deep decarbonization and electrification scenario studies [2,5–9] by uniquely providing a model intercomparison of net-zero scenarios [10–14]. The net-zero model comparison literature has expanded rapidly within the last few years [15]. Studies have gained insights on net-zero transitions through meta-analyses of the IPCC 1.5-degree scenarios [16] and other studies [17], expert perspectives [18], as well as literature reviews of individual studies [19], including a review of the U.S. net-zero literature [20]. The literature broadly agrees on the following points: (1) rapid adoption of solar and wind, often coupled with energy storage [21], is cost-effective, making the electricity sector the fastest and most significant source of emissions reductions; (2) widespread electrification of end-uses takes advantage of and supports the decarbonized power sector; (3) low- or zero-carbon alternative fuels will be needed to complement electrification; (4) end-use efficiency and dematerialization also play a role in reducing overall energy demand; (5) carbon dioxide removal strategies (i.e., direct air capture (DAC), bioenergy with carbon capture and sequestration (BECCS), and land-use, land-use change, and forestry (LULUCF)) will likely be necessary to achieve net-zero emissions and address residual emissions from hard to decarbonize sectors and remaining emissions from fossil fuel technologies with carbon capture and storage (CCS). Our paper adds to this literature by providing a model intercomparison of 16 detailed energy-economy models that reach net-zero CO_2 emissions by midcentury following a linear reduction pathway.

2. Scenario design and description

This paper examines three scenarios (Table 1): a Reference scenario, a net-zero CO_2 by 2050 scenario using default assumptions (Net Zero) and a net-zero scenario with optimistic decarbonization assumptions across four sectors: buildings, industry, transportation, and carbon management (i.e., CCS, DAC, and hydrogen) (Net Zero+) as described in the following sections.

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) [22] and the Inflation Reduction Act of 2022 (IRA) [23]. To the extent practicable, the reference scenario includes all other federal and state policies (e.g., carbon emissions signatures, renewable portfolio standards, the Regional Greenhouse Gas Initiative, or California's Global Warming Solutions Act of 2006 [AB32]). Modelers developed their own reference scenarios to be consistent with the assumption of no new climate policies. GDP and population are important drivers of energy and emissions (see SM1.1 and 1.2).[2] This scenario serves two functions in this study. First, it provides the perspective of the modeling teams on the future evolution of the economy and energy systems. Second, the reference scenario serves as a benchmark for comparison with the net-zero scenarios.

2.2. Net Zero scenario

The 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 DAC, BECCS, and natural carbon management options such as 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

[1] The United States has set goals of 100% carbon pollution-free electricity by 2035 and net-zero greenhouse gas (GHG) emissions economy-wide by 2050 and put forth the U.S. Long Term Strategy (LTS) which presents multiple pathways to a net-zero GHG economy by no later than 2050.

[2] Although population is an exogenous input to these models, for the CGE models in the study, GDP is an output.

Table 1
Scenario matrix.

	Sectors Buildings	Industry	Transportation	Carbon Management	Mitigation Pathway No Target	Net Zero by 2050
Default					Reference	Net Zero
Optimistic	+	+	+	+		Net Zero+

constant sink of 800 $MtCO_2$ per year is assumed.[3]

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 greenhouse gasses as considered in each model. In addition, we include a net-zero GHG by 2050 sensitivity scenario in the broader EMF 37 study to shed additional light on the differences between net-zero CO_2 and net-zero GHG targets.

Additional specifications to ensure model comparability across the net-zero scenarios 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 ensure 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, i.e., the marginal cost of abating an additional ton, as found in North America, 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. Net Zero+ scenario

The Net Zero+ scenario uses the same linear emissions reduction pathway as the Net Zero scenario, but with optimistic assumptions regarding the potential for electrification and decarbonization across the buildings, industry, transportation, and carbon management sectors. Modelers were provided the following guidance on the scope and nature of those assumptions.

Buildings: Two primary mechanisms for buildings decarbonization are electrification (contingent upon parallel decarbonization of electricity production) and efficiency. For buildings, the Net Zero+ scenario captures moderate increases in the scale, reach, and impact of current policies and programs (see SM3 for details). Under this scenario, electrification and efficiency adoption remain subject to market forces with plausible additional incentives, innovation, or other interventions that encourage more greater adoption. Building and appliances standards are also more aggressive, which raises the efficiency of new construction and equipment purchases. However, technology mandates, such as the prohibition of sales of fuel-fired equipment, are not widely enacted.

Industry: In industry, the Net Zero+ scenario represents greater technological change in four areas: (1) energy efficiency, (2) material efficiency, (3) electrification, and (4) use of biomass, hydrogen, and carbon capture and sequestration (CCS) in particular industries (see SM4). Enhanced energy efficiency lowers final demand for both electricity and non-electric energy. Greater material efficiency refers to a lower demand for materials from energy intensive processes via increased recycling and reuse and changes in product design. Material efficiency is applicable to the cement, paper, steel, plastics, aluminum, and glass industries. This narrative suggests greater electrification, particularly in low and medium temperature processes. Finally, models that do not endogenously represent fuel switching or CCS were encouraged to include greater use of these technologies. The guidance targets fuel switching to biomass in the chemicals, paper, and cement industries and switching to hydrogen in the steel and chemicals. Boyd and Worrell [24] offers quantitative guidance for plausibly optimistic implementation.

Transportation: The Net Zero+ transportation scenario includes more optimist assumptions about technology cost and availability, complementary policies, and consumer preferences (see SM5). Electric vehicle and battery costs fall more rapidly. Complementary policies, such as zero emission vehicle mandates, tighter emission standards, and changes in consumer incentives, are adopted. Greater availability of charging stations or refueling solutions lessen adoption barriers from range anxiety. Consumer preferences shift toward ride sharing and lower-energy modes of travel such biking and walking. Quantitative guidance on technology cost evolution was provided [25] (see SM5).

Carbon Management: Under the Net Zero+ scenario, the technology costs of all carbon management options decline (see SM6). Advances in CCS technologies lower the costs of carbon capture, transmission, and storage components, including the costs of biomass energy with CCS. Costs fall for hydrogen production, transportation, and end-use technologies (e.g., fuel cell vehicles). The same is true for direct air capture (DAC) costs. For a few key carbon management technologies (DAC, power sector CCS, hydrogen production), modeling teams were provided a set of technology cost and performance assumptions to use at their discretion (see SM6) but were ultimately free to characterize the technologies as they saw fit.

2.4. Caveats and limitations

Several observations are relevant for the interpretation of these scenarios. The Reference and Net Zero scenarios rely upon each models 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, and 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 layers additional assumptions, chosen by the modelers, about the cost and availability of electrification, mitigation, and carbon removal options. The Net Zero+ scenario description includes both quantitative and qualitative guidance to use more optimistic, where appropriate for that model, electrification and decarbonization assumptions across three end-use sectors and carbon management. Modelers had wide discretion over the implementation of the Net Zero+ guidance. Differences in the structure and assumptions of the models make it challenging to provide specific parametric guidance that meets all the modelers needs. Thus, the Net Zero+ scenario captures the modelers views on optimistic changes in technology, complementary policy, and consumer behavior that enable electrification and decarbonization. These results represent possible outcomes and should not be

[3] 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.

interpreted as probability distributions nor a full range of possible outcomes.

3. Models

The 16 models 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. Table 2 provides a summary of model characteristics. For additional details, refer to the linked model documentation and published papers cited in SM1.

4. Results

This section presents results for the 16 models that ran both the Reference and Net Zero scenarios, eight of which also ran the Net Zero+ scenario. Individual models may not appear in some figures because data were not reported.

4.1. Emission reductions

U.S. CO_2 emissions in the Reference scenario are projected to moderately decrease in most models, with emissions changes from 2020 to 2050 ranging from a 15% increase to a 56% decrease (Fig. 1).[4] Most models[5] project gross CO_2 emissions greater than 3000 Mt per year in 2050 in the Reference scenario. In the two net-zero scenarios, positive emissions from energy and industrial processes decline to around 1200 Mt CO_2 by 2050 in most models, with a few exceptions projecting over 2000 Mt CO_2. Positive CO_2 emissions reductions from 2020 to 2050 range from 34 to 80% in the Net Zero and Net Zero+ scenarios. Residual positive emissions are offset by large-scale deployment of negative emissions technologies, especially DAC and BECCS, and by assumed natural carbon sinks (LULUCF).

Across net-zero scenarios, power sector emissions are reduced by no less than 57% from 2020 to 2050, ranging from 59 to 100% lower emissions than in the Reference scenario by 2050 (Fig. 2), though only one model meets the U.S. 2035 Net-Zero goal for electricity sector CO_2 emissions (see SM1.3). By 2050 in the net-zero scenarios, there are few remaining residual emissions in the power sector (Fig. 2). Those residual power sector emissions are generally larger in the Net Zero+ scenario than in the Net Zero scenario. For about half of the models, reduction in power sector emissions in 2050 equals or surpasses the sum of the reductions across other energy sectors in the Net Zero scenario. With the addition of optimistic assumptions in the Net Zero+ scenario, buildings, industry, and transportation take up a greater percentage of emissions reductions. Three dynamics significantly contribute to these results: (1) optimistic assumptions in the Net Zero+ scenario lead to greater end-use emissions reductions, requiring less power sector mitigation to achieve net-zero, (2) optimistic assumptions lead to greater end-use electrification, which requires more output, and thus possibly greater emissions from the power sector, and (3) the Net Zero+ scenario projects increased availability and lower costs of carbon removal technologies that can offset unmitigated emissions.

Residual emissions in the net-zero scenarios in transportation are larger than in other sectors for most models, followed by industry and buildings emissions. Of the eight models that ran the Net Zero+ scenario, six show greater transportation emissions reductions than in the Net Zero scenario and four show greater industry and buildings emissions reductions than in the Net Zero scenario (see SM1.4).

Atmospheric removals are required to achieve net-zero emissions in all the models, ranging from just over 1000 Mt CO_2 per year on the low end to almost 3000 Mt CO_2 per year on the high end (about half of today's total GHG emissions). Fossil CCS technologies are used by nine models to allow combustion of fossil fuels with significantly reduced, but not eliminated, emissions (Fig. 3). Fossil CCS is deployed almost entirely to capture power sector combustion emissions from natural gas and coal, with minimal deployment in industry and hydrogen production, whereas BECCS deployment is more varied. For models that deploy BECCS, all project use in the power sector, but to different degrees, as well as alternative fuel production (biomass liquids and hydrogen) and industrial applications (see SM1.6–1.8 for detailed results on Fossil CCS and BECCS).

4.2. Carbon prices

Most models achieve the net-zero pathways by setting a CO2 emissions constraint.[6] Carbon prices, or marginal cost of an additional ton of reduction, vary across models due to differences in the costs of emissions reduction and carbon removal technologies and in the equilibrium mix of options deployed (Fig. 4). For the 11 models that provided carbon prices, nine report at least $400/tCO2 in 2050. Three models, EC-MSMR, ADAGE, and US-REGEN, report carbon prices in roughly the $100–$200/tCO2 range by 2050 in the Net Zero scenario. Carbon prices are reduced by 15–65% for the Net Zero+ scenario, relative to the Net Zero scenario, due to optimistic technology assumptions. In EC-MSMR and ADAGE, DAC sets the marginal cost of reductions. In US-REGEN, the marginal cost of reductions in equilibrium is set by BECCS, which provides both an alternative fuel and carbon sink.

4.3. Final energy

Final energy demand (Fig. 5) is projected to increase (2–33%) from 2020 to 2050 in the Reference scenario for all but four models (see SM1.9). AnyMOD[7] (−28%) and US-REGEN[7] (−19%) show the greatest reduction in final energy demand. To achieve net-zero CO_2 emissions, all models require a significant shift in composition of final energy. In the Net Zero and Net Zero+ scenarios, total final energy demand decreases by 6–35% from 2020 to 2050 across the models with four exceptions: ADAGE (+25%), FECM-NEMS (+10%), EC-MSMR (+6%), and MARKAL-NETL (+2%). Total final energy demand in 2050 decreases from the Reference to the net-zero scenarios in most models by 6–49% (MARKAL-NETL +9%, ADAGE +4%). Most of these reductions are derived from a switch to more efficient electric end-uses, of which more are available and at a lower cost in the Net Zero+ scenario.

There is a clear trend of increasing economy-wide electricity demand in the Reference scenario, and additional marginal increases in electricity demand in the Net Zero and Net Zero+ scenarios (Fig. 5). More than half of the models project increases in biomass-based fuels, and six project increased use of hydrogen. For those models that increase hydrogen use, the production methods vary. While some predominantly use electrolysis (EC-MSMR, EPA-TIMES, and EPS), others use natural gas steam methane reforming (with and without CCS) and biomass gasification with CCS (see SM.1.16).

The difference between the Reference and net-zero scenarios' final energy demands by sector and energy carrier is shown in Fig. 6. There is significant variation in fuel switching trends across sectors. There is strong consensus between models for buildings to transition away from

[4] Note that the models report different emissions for 2020. These differences can be attributed to different emissions datasets (i.e., EPA vs. EIA), base years, and calibration routines.

[5] AnyMOD projects much lower CO_2 emissions in its Reference scenario due to more optimistic assumptions for low-cost renewables and electrification options.

[6] The EPS model is an exception. EPS uses a combination of tax and subsidy policies to achieve the reduction targets instead of an absolute constraint on emissions.

[7] US-REGEN's reference scenario assumes more optimistic building and transportation electrification.

Table 2
Summary characteristics of model participating in EMF 37.

Model Name (Institution)	Spatial Resolution	Gas Coverage	Equilibrium approach & Foresight	Base-End Years; Timestep; Technology Choice	Carbon Management Options	Electric Sector	Buildings	Industry	Transport
ADAGE RTI International)	US+7 global regions	CO_2 & non-CO_2	General; Myopic	2010–2050; 5-year time steps; CES	DAC, Biofuels	11 technologies	Residential: 3 end-use Commercial: aggregated with other sectors	13 energy 24 non-energy sectors	8 modes, 1 vehicle class, power train options
AnyMOD (TU Berlin)	US, Canada, and Mexico	CO_2 only	Partial; Perfect	2020–2050; 5-year time steps; LP	BECCS, DAC, H_2	32 generation technologies, 4 storage technologies, 59 regions (49 states for the US)	Single building type	single industry sector	Passenger: 3 modes, Freight: 3 modes, 18 class/ powertrains
EC-MSMR (Environment and Climate Change Canada)	Canada, Mexico, US + 13 other regions	CO_2 & non-CO_2	General; Myopic	2014–2050, 5-year time steps; CES	BECCS (Electricity only), DAC, Green H_2, Biofuels, Renewable Natural Gas	13 technologies including backstops, 17 regions	Residential: included in households ommercial: single sector	4 energy 5 non-energy	2 modes (passenger included in household)
ENERGYpathways AND RIO (eVOLVED eNERGY)	27 US regions corresponding to EPA eGRID (aggregation of zones in Alaska and Hawaii)	CO_2 & non-CO_2	Partial; Perfect	2021–2050; 5-year time step; Mixed; LP in electricity and fuel, logit in end-use	BECCS, DAC, H_2, H_2 storage, Biofuels, Synthetic Gas & Liquids, Ammonia (38 fuel conversion/ storage technologies)	27 regions; 62 technologies; 960 time periods (40 day samples w 24 sequential hours)	Residential - 16 end-uses x 3 building types; Commercial - 12 end-uses x 11 building types	20 industrial subsectors x 8 service categories (heat, hvac, lighting, machine drives, refrigeration, support, transport, and other)	14 modes, 44 class/ powertrains
EPA-TIMES USEPA/ORD)	9 US regions	CO_2 & non-CO_2	Partial; Perfect	2010–2050, 5-year time steps; LP	BECCS (Electricity only), DAC, H_2, Biofuels	24 technologies; 9 US regions	Residential: 7 end-uses Commercial: 9 end-uses	20 sectors	2 modes, Light-duty: 9 classes, 10 powertrains Heavy-duty: 9 classes, 10 powertrains
EPS (Energy Innovation)	US	CO_2 & non-CO_2	Partial; Myopic	2020–2050, 1-year time steps; Logit	DAC, H_2, Biofuels	16 technologies; 1 region	Residential: uban & rural Commercial: single 6 end-uses	25 manufacturing sectors (including energy)	6 modes, 2 classes, 7 power trains
FARM (USDA)	US, Canada + 11 other world regions	CO_2 only	General; Myopic	2011–2101, 5-year time steps; Mixed: Logit for electricity generation shares; CES otherwise	BECCS, Biofuels	10 technologies; 1 region	Residential: single Commercial: single	6 energy-intensive; 1 other industry	3 modes (land, air, water); Fuels for land include petroleum, biofuels, electricity
FECM-NEMS & OP-NEMS (OnLocation)	US; subnational aggregation varies by submodule	CO_2 only	Partial; Near-perfect (electricity, liquid fuels), Myopic (demand)	2021–2050; 1-year time steps; Mixed: LP in power and liquid fuels; MIP for CO_2 pipeline and storage; Logit in demand models	BECCS (electricity only), DAC, CCS for ethanol, natural gas processing, H_2 in refineries and cement; liquid biofuels	24 new tech, 3 CCS retrofit techs, plant-level database for existing techs, and 25 NERC-based regions.	Residential: 3 types, 12 end-uses ommercial: 11 types, 10 end-uses 9 Census regions	15 manufacturing6 non-manufacturing plus refining 4 Census divisions.	8 modes, 16 LDV classes, commercial light trucks and 3 freight classes, 10 power trains
GCAM (PNNL)	Canada, Mexico, US, +29 other regions	CO_2 & non-CO_2	Partial; Myopic	2015–2100; 5-year time step; New investment: logit based on expected profitability;	BECCS (electricity, biofuels, H_2 with CCS), DAC, H_2 in end-use, liquid	23 technologies; 9 fuels; single market per region	Residential: US 14 end-use Commercial: US 10 end-use ROW end-use 3	6 manufacturing 3 non-manufacturing	Passenger: 6 modes, 4 classes, 11 power trains. Freight: 3 modes, 3 HDV classes,

(*continued on next page*)

Table 2 (*continued*)

Model Name (Institution)	Spatial Resolution	Gas Coverage	Equilibrium approach & Foresight	Base-End Years; Timestep; Technology Choice	Carbon Management Options	Electric Sector	Buildings	Industry	Transport
				Existing technologies must cover operating costs.	biofuels, biogas				14 power trains
GCAM-USA (PNNL/ University of Maryland)	50 US states, Canada, Mexico+29 other regions	CO_2 & non-CO_2	Partial; Myopic	2015–2100; 5-year time step; New investment: logit based on expected profitability; Existing technologies must cover operating costs.	BECCS (electricity, biofuels, H_2 with CCS), DAC, H_2 in end-use, liquid biofuels, biogas	23 technologies; 9 fuels; 50 states+DC; trade in 15 grid regions (NERC-like); 4 segment load duration curve	Residential: USA 14 end-use Commercial: USA 10 end-use ROW end-use 3	3 (Cement, Fertilizer, and All Other Industry)	Passenger: 6 modes, 4 classes, 11 power trains. Freight: 3 modes, 3 classes, 14 power trains
gTech (Navius Research)	Canadian Provinces + US	CO_2 & non-CO_2	General; Myopic	2015–2050; 5-year time steps; CES	DAC, BECCS, H_2, Biofuels	16 technologies; 11 regions	Residential: 3 shell types, 11 end-uses Commercial: 6 shells types, 6 end-uses	34 non-energy industrial sectors 9 agriculture & forestry sectors 24 energy sectors	5 modes, 6 classes, 11 power trains
MARKAL-NETL (NETL)	9 US Census regions	CO_2 & non-CO_2	Partial; Perfect	2005–2075; 5-year time steps; LP	BECCS, DAC, H_2, Biofuels, Synthetic Gas & Liquids	45 technologies, 9 regions	Residential: 8 end-uses Commercial: 12 end-uses	7 non-energy, 9 industrial energy carriers	3 modes, 9 classes, 10 power trains
NATEM (Esmia Consultants)	13 Canadian regions; 9 US Census regions + CA, TX, NY; Mexico	CO_2 & non-CO_2	Partial; Perfect	2016–2060; 2- to 5-year time steps; LP	BECCS, DAC, H_2, Biofuels, Synthetic Gas & Liquids	US: 90 technologies, 12 regions	US Residential: 8 end-uses Commercial: 12 end-uses	7 non-energy 8 industrial energy carriers	6 modes, Passenger: 3 classes, 9 powertrains Commercial: 3 classes, 9 powertrains 15 fuels
TEMOA (North Carolina State University)	9 US regions	CO_2 only	Partial; Perfect	2020 to 2050; 5-year time steps; LP	BECCS (electricity only), DAC, H_2, Biofuels, Synthetic fuels	3 storage technologies; 15 generation technology types; 9 regions	Residential: 10 end-uses Commercial: 8 end-uses	2 sectors Manufacturing: 9 end-uses Non-manufacturing: 6 end-uses	6 modes, Passenger: 1 class, 4 powertrains Commercial: 2 classes
US-REGEN (EPRI)	16 US regions	CO_2 & non-CO_2	Partial; Perfect	2015–2050; 5-year time steps; Mixed; LP in electric and fuels sectors, logit in end-use sectors	BECCS, DAC, H_2, Biofuels, Synthetic Gas & Liquids, Ammonia	16 regions; 94 technologies; 120 representative hours / hourly dispatch	Residential & Commercial sectors 2 size categories plus vintages and climate zones 6 end-uses	37 non-energy sectors	36 vehicle classes/ powertrains
USREP-ReEDS (MIT-NREL)	USREP: 12 US regions ReEDS: 134 balancing areas	CO_2 & non-CO_2	General; Myopic	2017–2100; 5-year time steps; Mixed; CES in USREP; LP in ReEDS	BECCS (Electricity only), DAC, Biofuels	58 technologies 134 balancing areas (CONUS) 17 time slices	Residential & Commercial Production function with 3 fuels	5 energy 6 non-energy	2 modes, Passenger: 3 classes; Non-passenger is aggregated into a single sector

Notes: LP = linear program, CES = Constant Elasticity of Substitution, BECCS = biomass energy with carbon capture and sequestration, DAC = Direct Air Capture, H2 = hydrogen.
Additional model information (unique attributes, website, and references) may be found in Table SM1.

natural gas and total buildings final energy demand decreases significantly. For transportation, the predominant switch is away from oil, mostly towards electricity, and to a lesser extent, biofuels (and significant use of hydrogen in EC-MSMR and EPA-TIMES), with large variation across models. Final electricity demand in transportation tends to be much smaller than the oil replaced, due to the much higher efficiency of electric vehicles compared to internal combustion engines. The least consensus occurs in industry, where there is more variation across models in total final energy demand as well as the fuel mix. However, almost all models show reductions in industrial gas demand compared to the Reference scenario. Like trends in transportation, some models electrify industry while others adopt biomass-based fuels and hydrogen. It is important to note that end-uses may be electrifying even if electricity demand in total doesn't increase, due to countervailing effects of energy-efficiency. Additionally, Fig. 6 highlights the differences in final energy demand from the Reference scenario, in which some models (namely AnyMOD and US-REGEN, see Fig. 7) already project significant electrification.

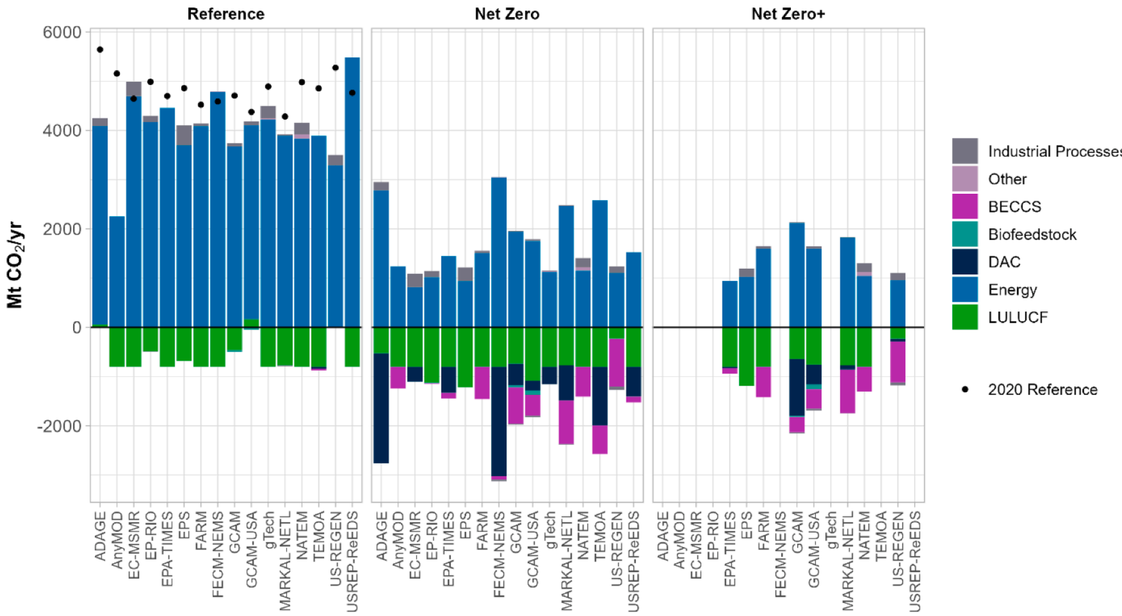

Fig. 1. CO_2 Emissions in 2050 for Reference, Net Zero, and Net Zero+ Scenarios. The stacked bars in this figure show 2050 reported CO_2 emissions, by model, for the Reference, Net Zero, and Net Zero+ scenarios. The points in the Reference panel show gross 2020 energy and industrial process emissions from the Reference scenario. Industrial process emissions are only presented for models that include them. ADAGE, EP-RIO, EPS, GCAM, GCAM-USA, and US-REGEN do not use the exogenous assumption for the carbon land sink (−800 Mt CO_2/yr). US-REGEN reports only marketed land-based carbon offsets, not a full land sink.

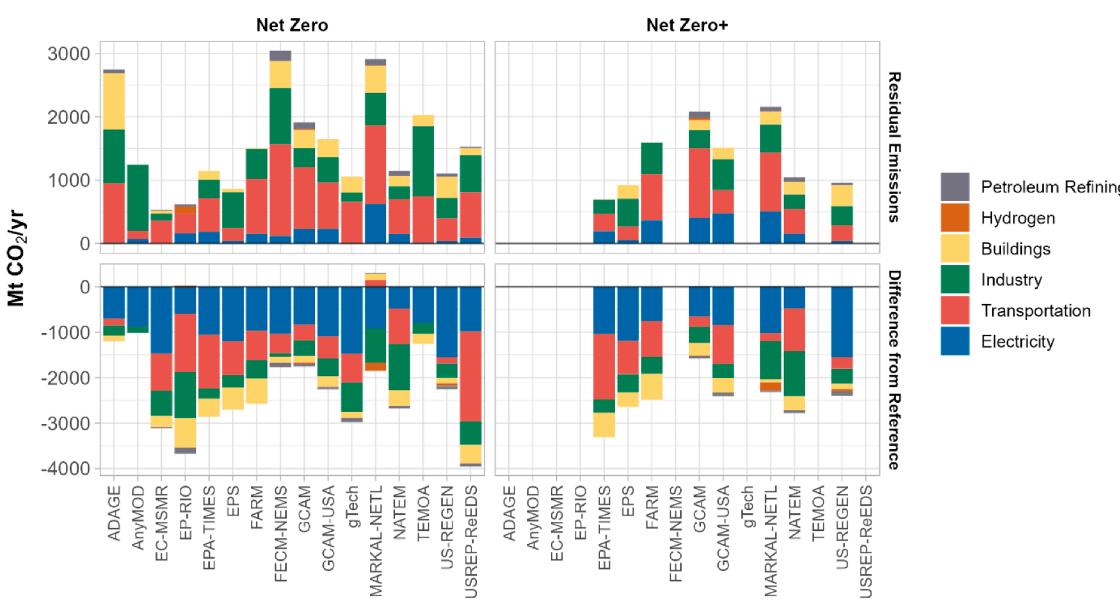

Fig. 2. Sectoral CO_2 Emissions for Net Zero Scenarios in 2050. The top panel stacked bars show residual sectoral emissions in the Net Zero and Net Zero+ scenarios. Transportation and industry have the largest variation in emissions between models. The lower panel stacked bars show the difference in sectoral emissions from the Reference scenario to the Net Zero and Net Zero+ scenarios. Most models show reductions in gross emissions across the buildings, industry, and transportation sectors, with the largest reduction in the power sector, as compared to the Reference scenario. See SM1.4 for difference between Net Zero and Net Zero+ residual emissions.

4.4. *Electrification*

Reduction in final energy demand in the net-zero scenarios, across the economy and by sector, is driven largely by a switch away from fossil fuels to electricity and other non-emitting fuels. Electrified end-uses are typically more energy efficient and, additionally, the Net Zero+ scenario assumes lower-cost energy efficiency, further reducing energy demand. Those final energy efficiency gains are not necessarily present for all non-electric low-carbon fuels. As shown in Fig. 7, current levels of electrification vary widely between sectors, from less than 1% in transportation to almost 50% in buildings.

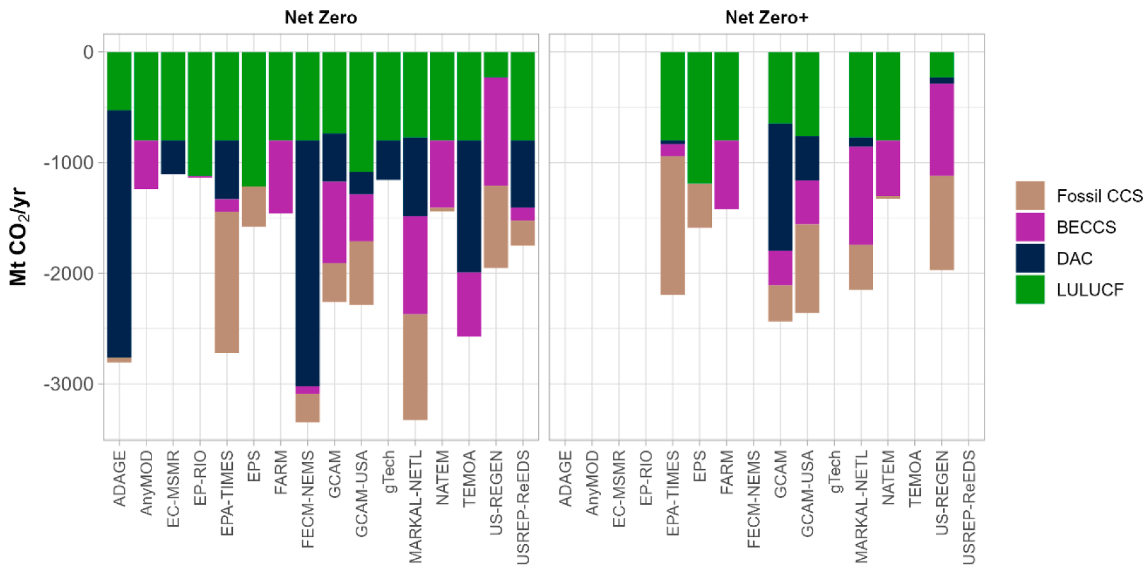

Fig. 3. Carbon Sequestration in 2050. Carbon sequestration includes carbon dioxide removal technologies (i.e., DAC, BECCS, LULUCF) and carbon capture technologies (i.e., Fossil CCS). ADAGE, EP-RIO, EPS, GCAM, GCAM-USA, and US-REGEN do not use the exogenous assumption for the carbon land sink (−800 Mt CO_2/yr). US-REGEN reports only marketed land-based carbon offsets, not a full land sink.

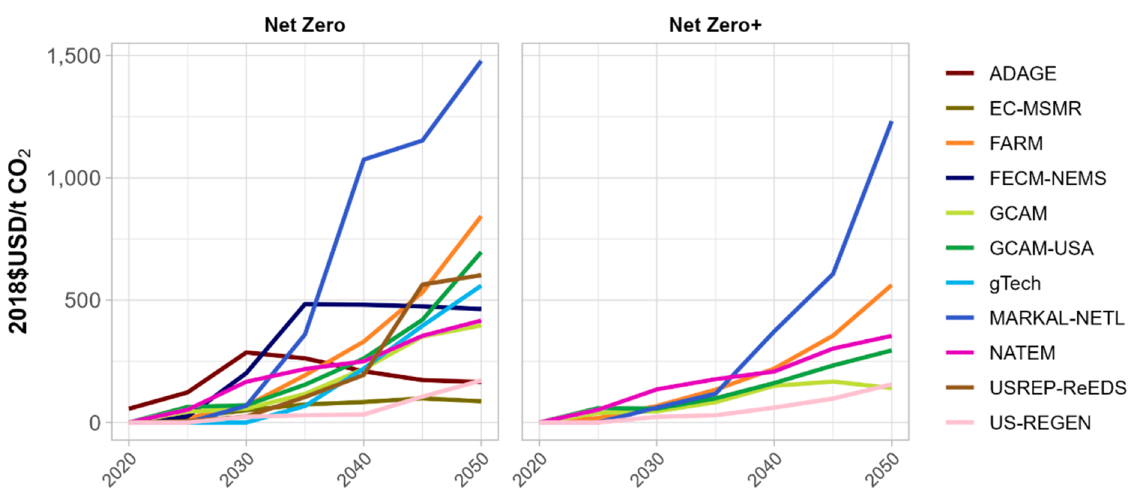

Fig. 4. Carbon Prices Over Time. Carbon prices are applied to all carbon emissions economy-wide, including credits for carbon negative solutions. Carbon prices tend to be lower in the Net Zero+ scenarios due to more optimistic future technology assumptions that lead to cheaper mitigation and carbon removal options.

All models, except for AnyMOD,[8] project only a modest increase in total electricity share in final energy by 2050 in the Reference scenario, driven mostly by increased electrification of transportation and buildings. Across both net-zero scenarios, there is a much steeper increase in electrification from 2020 to 2050 than in the Reference Scenario, averaging 74% electrification in buildings (55–99%), 32% electrification in industry (13–59%), and 31% electrification in transportation (6–81%), leading to an average of 43% total end-use electrification (21–60%) by 2050. While the average increase in 2050 electrification between the Reference and Net Zero scenarios is roughly equal between sectors (+10–13 percentage points (p.p.), the marginal increase between the Net Zero and Net Zero+ scenarios is far larger in transportation than in buildings or industry (+10 p.p. in transportation, +2 p.p. in buildings, −4 p.p. in industry). Factors impacting the extent of electrification vary by model, including availability of electric alternatives across transport modes and industrial processes, rate of stock turnover, relative cost for electric technologies across applications, and technical, institutional, or behavioral deployment limits.

To meet higher demands for electricity under net-zero targets (Fig. 5), generation from emissions-free technologies increases. Solar[9] and wind comprise most of the added generation for all models, though some models adopt modest increases in nuclear and hydro, and a small number increase biomass generation. By 2050, most models are

[8] AnyMOD exhibits very aggressive electrification of transportation and buildings with over 75% of final energy coming from electricity in transportation and nearly 100% in buildings by 2050 in the Reference scenario. AnyMOD's high electrification is mainly driven by the fact that renewables and electrification are already cost efficient for a lot of applications in the Reference scenario without any price or constraint on carbon within their model. In transportation, the model does not make exogenous assumptions or impose constraints on the development of electric vehicles and electric vehicles for passenger and freight road transport reach cost parity with internal combustion engine vehicles by 2025.

[9] EC-MSMR increase in solar generation is majority solar thermal generation (see SM1.15).

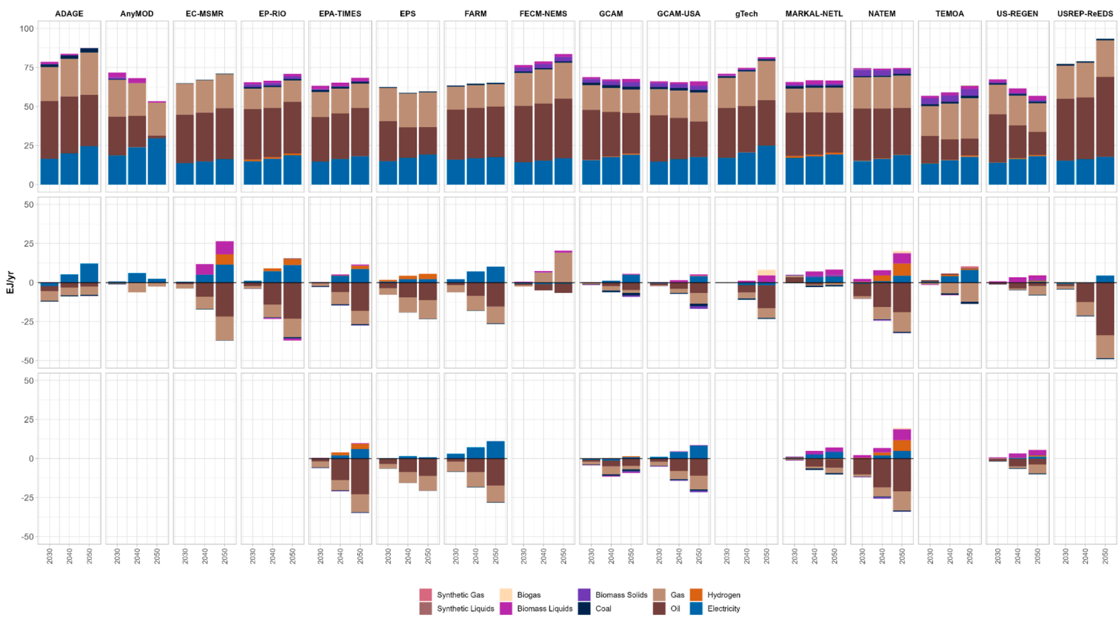

Fig. 5. Final Energy by Fuel Over Time. This figure shows absolute final energy by fuel for the Reference scenario in the top panel. The bottom two panels show the difference between the Net Zero and Net Zero+ scenarios and the Reference scenario. Note: The value range differs from the Reference and Net Zero scenario panels, but the magnitude is equal.

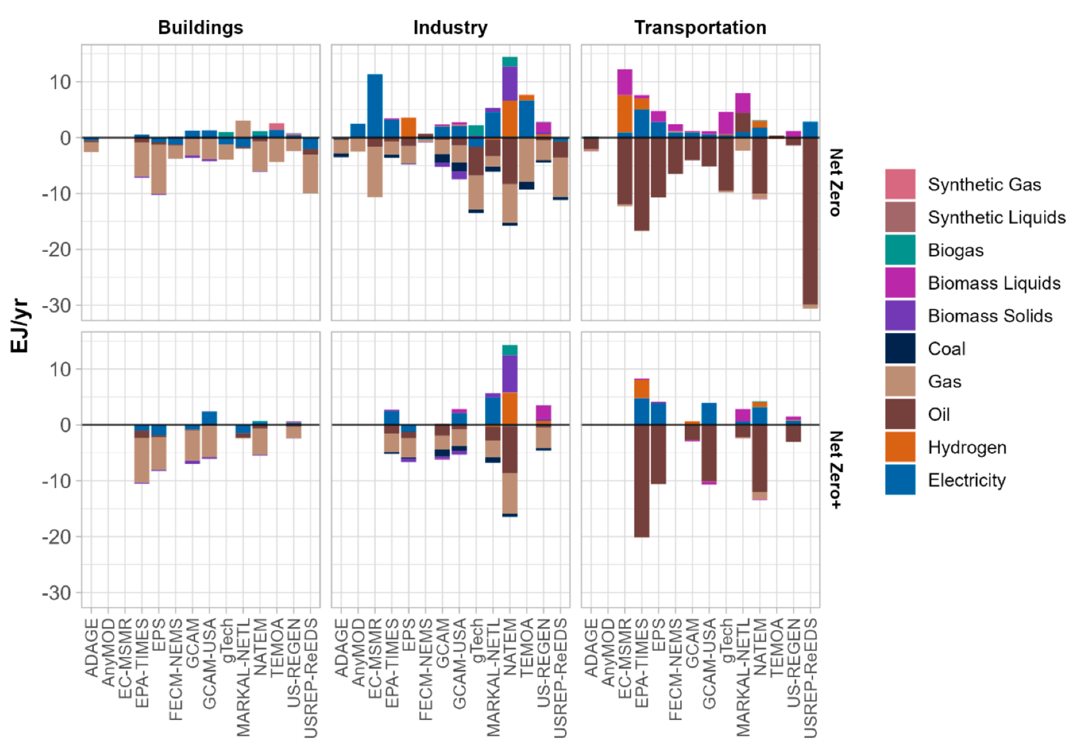

Fig. 6. Final Energy by Sector, Difference from Reference in 2050. This figure shows the difference in 2050 final energy by fuel from the Reference scenario to the Net Zero and Net Zero+ scenarios. ADAGE, EC-MSMR, gTech, US-REGEN, and USREP-ReEDS did not submit results for the Net Zero+ scenario. See Figure SM1.10–1.12 for absolute values.

capturing 100% of the combustion emissions from biomass generation as well as those from fossil combustion (see SM1.14). CCS is added for remaining fossil generation, but fossil retirements outweigh these additions, which leads to net decreases in fossil electricity generation. There is a significant increase in total electricity generation in the Net Zero scenario for most models despite a decrease in generation from fossil fuels (Fig. 8). For all models but GCAM-USA, total electricity generation increases relative to the Reference scenario in the Net Zero+ scenario, but to a lesser extent than in the Net Zero scenario.

4.5. Net zero pathways

These U.S. net-zero CO_2 emissions scenarios exhibit many similarities in their qualitative insights about key decarbonization strategies. This includes (1) the central role of the power sector in direct emissions reductions and supporting end-use mitigation through electrification,

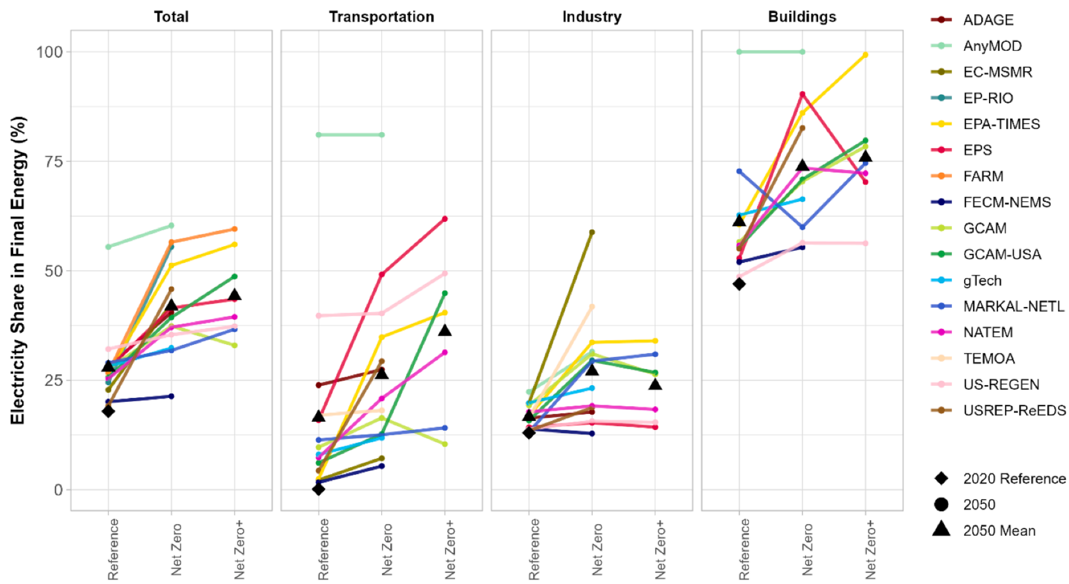

Fig. 7. Percent Electricity of Final Energy by Sector for the Net Zero Scenario in 2050 with Reference values for 2020. Results shown are the percent that electricity makes up of total final energy by sector in 2050. The asterisks show the 2020 reference value (AEO 2021).

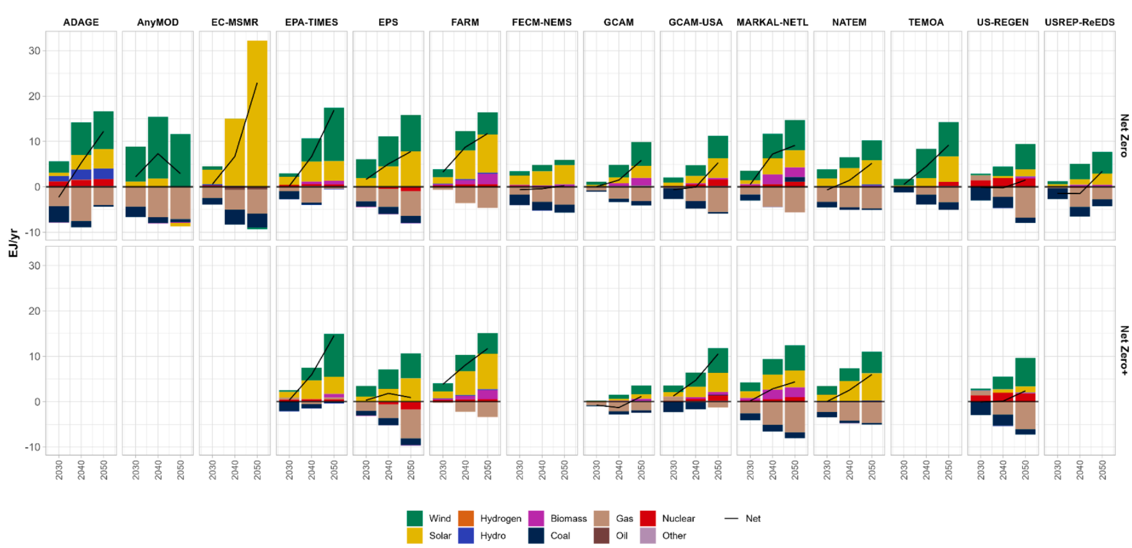

Fig. 8. Electricity Generation Mix by Energy Source, Difference from Reference Over Time. This figure shows the net difference in electricity generation by technology between the Reference scenario and the Net Zero and Net Zero+ scenarios. The line shows the net difference in total generation for each model from the Reference for the net-zero scenarios. See figure SM1.13–1.15 for absolute values and CCS break-outs.

(2) the importance of other low or zero-carbon fuels, such as biofuels and hydrogen, for end uses that are more difficult or costly to electrify, (3) increases in energy efficiency, and (4) large-scale deployment of carbon removal options. These common features generally align with net-zero scenarios in the literature from the U.S. and other countries (Fig. 9, below). This study extends the existing literature by conducting harmonized net-zero scenarios for the U.S. across a greater range of models and assumptions.

Despite the similarities in qualitative insights, there is considerable variation in magnitudes of these effects across models (Fig. 9). Some of these differences are due to input assumptions, which are explored in the optimistic cost sensitivity (Net Zero+). Fig. 9a illustrates how the extent of electrification and electricity demand varies across participating models. Electricity's share of final energy increases from just over 20% today to 21–60% in 2050 under a net-zero policy, while electricity demand grows by 20–150% during this period. These magnitudes are consistent with earlier literature.

Fig. 9b compares residual emissions and the extent of reductions in fossil fuel consumption across models in this study relative to earlier net-zero scenarios, highlighting the reliance on negative emissions technologies. Some models have very low residual emissions and fossil fuel use, while others retain fossil fuels and either capture emissions or offset them with carbon removal.

Higher rates of gross CO_2 emission reductions (see Fig. 10; e.g., those above 4% per year) mean less reliance on removal technologies (see Fig. 1). Slower changes in fossil energy demand over time (e.g., ADAGE, FECM-NEMS, MARKAL-NETL) correspond with greater use of CO_2 capture and removal technologies (i.e., >1 $GtCO_2$/year; see Fig. 3). It is important to note, however, the considerable uncertainty about the feasibility and reliability of carbon removal and extent of fossil fuel reductions in reaching net-zero emissions. Scaling a direct air capture industry from megatons to gigatons requires extremely rapid growth and innovation [26].

The models also show a wide range of sensitivity to the effect of

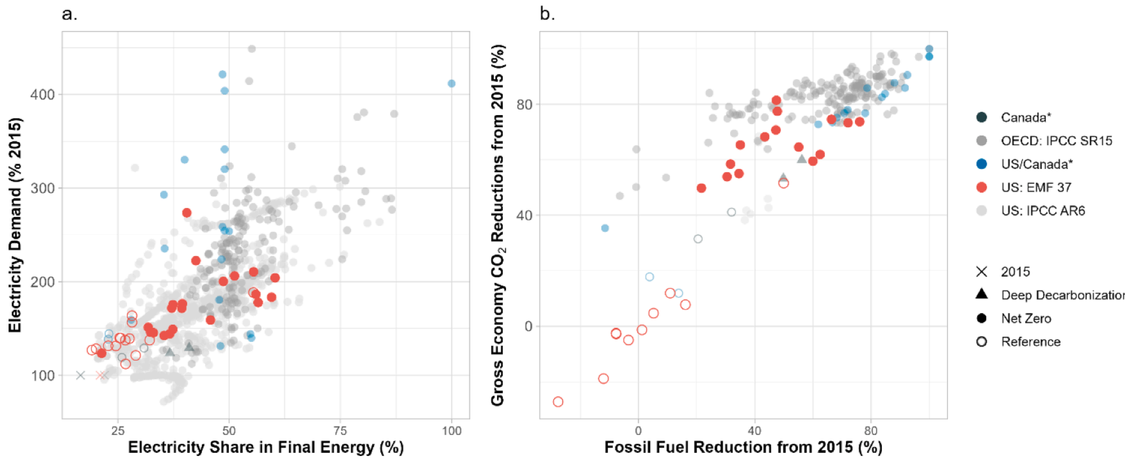

Fig. 9. 2050 Performance Indicators for Net Zero and Literature Deep Decarbonization Scenarios. These figures present EMF 37 results in the context of the literature [17] (denoted with an asterisk * in the legend) and International Panel on Climate Change (IPCC) reports for the year 2050. IPCC AR6 results are only shown for scenarios that achieve net-zero CO_2 emissions by 2050. a) Electrification. Deep decarbonization and net-zero scenarios rely heavily on electrification. This figure shows the relationship between electrification of end-uses and electricity demand. b) Fossil fuel use (primary energy). Reductions in fossil fuel use versus recent history (x-axis) correspond to overall CO2 reductions. Lower reductions in gross emissions (y-axis) mean achieving net-zero emissions or deep decarbonization requires additional carbon capture and removal. *Note that some EMF 37 models do not appear in Fig. 9 due to missing data.

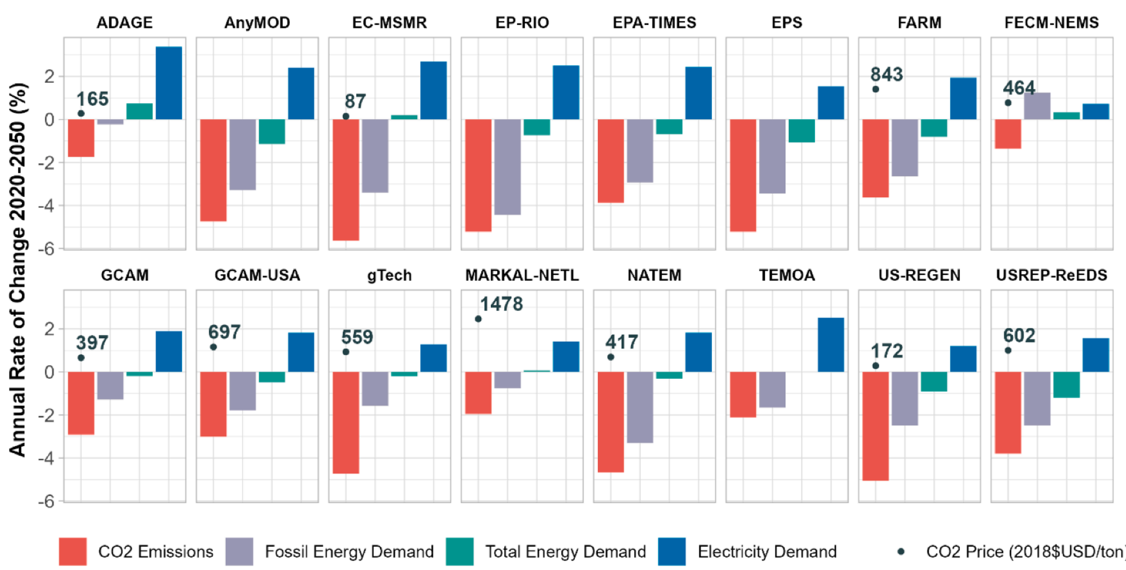

Fig. 10. Annual Growth Rates 2020–2050 and 2050 Carbon Price, Net Zero Scenario. This figure shows the annual growth rates 2020–2050 in the Net Zero scenario for economy-wide gross CO_2 emissions, total final energy demand, fossil final energy demand (coal, natural gas, oil/petroleum), and electricity demand. Carbon prices are shown for models reporting them.

carbon prices on final energy demand. For example, final energy demand grows in FECM-NEMS ($464/t$CO_2$) and MARKAL-NETL ($1478/tCO_2) yet falls in other models with lower prices (e.g., NATEM and US-REGEN). Additionally, carbon prices do not necessarily correlate with emissions reductions. Differences in these sensitivities call out several potential pathways towards achieving net-zero CO_2 emissions. These pathways are distinct in their degree of electrification, electricity demand changes (and electricity generation mix), fuel switching, and utilization of carbon removal technologies (i.e. DAC and BECCS).

These results have important implications for energy system planners. The extent of fossil fuel consumption and production (Figs. 9, 10) has significant impacts on regional economies and ancillary benefits (e.g., air quality co-benefits). Power system planners and technology developers have more granular information about potential markets and technology competitiveness under net-zero policies, though cross-model variation in projected fossil fuel consumption underscores the importance of future research and risk management. In addition, differences between Reference and net-zero scenarios show deployment gaps that would be met through future actions and policies. These are sometimes differences in the pace and magnitude of changes (e.g., transport electrification that occurs in the Reference is amplified by net-zero policies, per Fig. 9), while in other instances involves entirely different strategies (e.g., deploying low-carbon fuels and carbon removal).

5. Conclusions and extensions

5.1. Conclusions

The deep decarbonization and high electrification transitions investigated in EMF 37 come in the context of several recent policy commitments and company targets. The 2021 U.S. Nationally Determined Contribution as part of the Paris Agreement has a long-term goal of reaching net-zero emissions by 2050 across all GHGs. The scenarios in this study help to illustrate pathways toward this target, though an all

GHG target is more stringent than the net-zero CO_2 ones studied here, and given high marginal abatement costs of some non-CO_2 GHGs, these all-GHG net-zero scenarios could entail greater electrification, carbon removal, and other mitigation approaches [27,28]. Several states have policies and targets for reaching net-zero emissions in CO_2 and GHG terms, in some cases only for a subset of sectors like electricity,[10] while companies also are setting net-zero emissions targets.[11] This study can inform these targets and their implications for different stakeholders, including showing different rates of emissions reductions across sectors, allocation of residual emissions across sectors and regions, and magnitudes of policy stringency to reach net-zero emissions.

This paper finds broad agreement in energy system trends across models towards deep decarbonization of the power sector, coupled with increased end-use electrification of buildings, transportation, and to a lesser extent industry. These findings are consistent with much of the existing literature on deep decarbonization and electrification. Disparate model structure and sources for input assumptions affect the speed and magnitude of these trends. Across net-zero scenarios by 2050 scenarios, all models show a reliance on negative emissions technologies to offset residual emissions, which remain primarily in the transportation and industrial sectors. The land sink is projected to offset ~50% or more of residual emissions for most models, with direct air capture and bioenergy with carbon capture and storage offsetting the rest.

Important differences emerged in the results, showing divergent pathways to net-zero among end-use sectors with electrification and grid decarbonization as necessary but not sufficient conditions to achieve net-zero CO_2 emissions. The buildings sector achieves a high level of electrification though there is only modest, if any, increase in electricity use due to increased energy efficiency. All models see a reduction in natural gas use in buildings. Decarbonization pathways for industry and transportation differ more greatly between models. All models project decreased use of petroleum and natural gas, but replace them with a different mix of electricity, hydrogen, and biomass-based fuels. Increased electrification across sectors requires power sector capacity additions, all of which are met by renewable and other emissions-free sources, paired with some adoption of carbon capture for fossil fuel power plants. Carbon prices vary across models due to cost differences of emissions mitigation options within sectors and for removal technologies but are reduced by all models with the optimistic technology assumptions, which lower the cost of mitigation by 15–65%.

This paper does not posit which pathway to net-zero is most plausible, cost-effective, or beneficial. There remains great uncertainty in the potential for many relatively nascent technologies (e.g., DAC and hydrogen) and behavioral changes, evidenced by the divergent pathways presented in this study. Not all low-carbon pathways and technologies are represented in all models. Even when represented, the use of individual technologies often differs between models. The distribution of the results presented in this study reflect the complexity of projecting the evolution of the energy system and its emissions through mid-century. There is a need to revisit these representations and assumptions over time as technologies evolve. However, the broad agreement across models, discussed above, provides a foundation for further analysis of net-zero pathways.

5.2. Extensions: forthcoming EMF 37 publications

This paper serves as an introduction to EMF 37 as a whole and an executive summary of high-level results for the United States. Following the publication of this paper, the analysis and insights from EMF 37 will be presented in three sets of papers: (1) study group papers focusing on sectoral considerations across models for buildings, industry, transportation, and carbon management (e.g. alternate assumptions about technologies, markets, and policies (SM 3–6), (2) cross-cutting analyses focusing on individual technologies and topics, including the electricity sector, hydrogen, bio-fuels, trade, household distributional and equity outcomes, ancillary impacts (e.g., criteria air pollution), and comparisons with international modeling exercises, and (3) individual modeling team papers. Additional reference scenarios that represent the BIL and IRA are included in an expanded set of scenarios (SM 2) that will be included in a subset of these papers to measure the impact of these new legislation and highlight key measures that may change the near-term emissions trajectory, energy mix, and cost of decarbonization. This effort is a significant addition to the growing analyses on the impact of the BIL and IRA [29–31]. These papers will present a more detailed picture of EMF 37 results from sectoral, technical, policy, macro-economic, international, and equity perspectives, both across models and for individual models.

Supplementary materials

Several supplementary documents have been provided. SM1 contains additional figures and information on participating models. SM2 contains the EMF 37 study design document. SM3 through SM6 contain further guidance from the Building, Industry, Transportation, and Carbon Management study groups, respectively.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

James McFarland, Allen Fawcett, John Weyant, Trieu Mai, and Geoff Blanford are all editors for the special issue for which this manuscript is being submitted.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2023.100104.

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