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Policy implications of net-zero emissions: A multi-model analysis of United States emissions and energy system impacts

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ABSTRACT

Many countries, subnational jurisdictions, and companies are setting net-zero emissions goals; however, questions remain about strategies to reach these targets, policy measures, technology gaps, and economic impacts. We investigate the potential policy implications of reaching economy-wide net-zero CO_2 emissions across the United States by 2050 using results from a multi-model comparison with 14 energy-economic models. Model results suggest that achieving net-zero CO_2 targets depends on policies that accelerate deployment of zero- and low-emitting technologies that have seen rapid cost reductions in recent years (including wind, solar, battery storage, and electric vehicles) as well as relatively nascent options (including carbon capture and storage, advanced biofuels, low-carbon hydrogen, advanced nuclear, and long-duration energy storage). While net-zero policies are likely to lower fossil fuel consumption, including considerable coal and petroleum reductions, achieving net-zero emissions does not necessarily mean phasing out all fossil fuels. Model results indicate that the Inflation

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Reduction Act's energy and climate provisions amplify near-term decarbonization but that net-zero policies have larger impacts on long-run outcomes. Stringent climate policy can have large fiscal impacts on tax revenue and government spending—revenues from carbon pricing and subsidies for carbon removal range from 0.1 % to 3.7 % of GDP in 2050 across models. Each dollar per metric ton carbon price leads to a 0.06 % to 0.31 % reduction in economy-wide CO_2 emissions relative to a reference scenario with current policies. Spending on energy across the economy decreases relative to today for many models under reference and net-zero policies, especially as a share of GDP, due primarily to end-use electrification and energy efficiency.

1. Introduction

Many countries, subnational jurisdictions, and companies are setting net-zero emissions goals, where removals balance anthropogenic emissions of CO_2 or greenhouse gases (GHGs). From a physical science perspective, further warming essentially stops when global CO_2 emissions reach net-zero levels, and limiting global warming to specific temperature levels requires reaching net-zero CO_2 with deep reductions in other GHG emissions [1–3]. Despite the increasing prevalence of net-zero targets, uncertainty remains regarding policy and technology strategies to reach these goals as well as in the environmental and economic impacts of these strategies on consumers and society.

Although there are modeling studies that investigate strategies to reach net-zero emissions in the U.S., many analyses focus on results from a single model [4–9]. In contrast, model intercomparisons run harmonized scenarios across a range of models with different structural features and different input assumptions such as technology costs, fuel prices, and financing. This approach helps decision-makers identify findings that are robust across models and scenarios, areas of uncertainty, and the relative influence of structural and parametric uncertainties on model outputs [10].[1] Multi-model comparisons are important for understanding net-zero energy systems, since transformational changes to reach decarbonization targets can lead to disagreement among experts in how to model increasingly integrated systems, technological cost and performance assumptions for emerging technologies, and policy responses by firms and households. Comparisons of net-zero energy systems in the U.S. and other countries from scenario databases often do not use harmonized scenarios or provide common reporting, which makes comparisons challenging [11–13].

This paper investigates the potential environmental and economic impacts of achieving economy-wide net-zero CO_2 emissions across the United States by 2050 using results from a multi-model comparison with 14 energy-economic models. The analysis highlights technology and sectoral gaps in reaching net-zero CO_2 relative to current policies and market trends. This paper is part of the Energy Modeling Forum (EMF) 37 study, which explores deep decarbonization and high electrification scenarios in North America. A preliminary overview paper for the study was published in 2023 [14]. This paper builds on that analysis by integrating finalized runs that reflect updates from modeling teams and more recent scenarios that include policy developments since that article's publication, namely the Inflation Reduction Act (IRA), which includes decarbonization incentives across a range of areas [15–17]. These results can offer insights to policy-makers and other decision-makers seeking to bridge the gap between current efforts and emissions goals, technology developers and investors seeking to understand the relative competitiveness of technologies under different policy conditions, energy companies projecting future demand drivers, and researchers updating their models to capture decarbonization policy and technology pathways. This paper aims to summarize insights from the EMF 37 study for broader audiences, including policy-makers, technology developers, the public, and other stakeholders. More technical discussions for modelers, researchers, and other audiences are provided in EMF 37 deep dive papers on electricity, transport, industry, carbon management, hydrogen, bioenergy, and air quality [18–24].

2. Methods

Model intercomparison studies are used in a range of fields including climate science and energy modeling to understand differences in model methods, data, and outputs [25]. Such multi-model studies help to identify robust insights across a variety of structural and parametric uncertainties as well as to quantify areas of disagreement. EMF was established at Stanford in 1976 and has a long history of bringing together leading modelers, experts, and decision-makers to investigate important energy and environmental issues. The EMF 37 study brings together state-of-the-art energy-economic models to understand deep decarbonization and net-zero pathways for the U.S. and North America, including the roles of technological and behavioral change in electrifying transportation, buildings, and industry.

2.1. Scenario design

This analysis focuses on four policy scenarios:

- **Reference:** The reference scenario is driven by economic fundamentals along with existing policies, regulations, and incentives. This scenario incorporates federal and state policies in effect from early 2022 (i.e., when the EMF 37 overview paper scenarios were finalized), including state-level power sector portfolio standards and state-level economy-wide CO_2 policies such as those in California (see Appendix A1.2). Counterfactual reference scenarios are useful in policy analysis, as they isolate the impacts of proposed policies from background changes in technologies, markets, existing policies, and other drivers.
- **Reference with IRA:** This updated reference scenario includes energy and climate provisions of IRA and the Infrastructure Investment and Jobs Act (IIJA), which are summarized in Appendix A1.2.
- **Net-Zero:** This scenario reaches economy-wide net-zero CO_2 emissions by 2050 (Fig. 1).[2] This national target focuses on CO_2 emissions only, including emissions from fossil fuel combustion and industrial processes, and can include negative emissions from carbon dioxide removal (CDR) approaches along with carbon capture and sequestration (CCS) technologies that separate and capture CO_2 at the point of production. CDR encompasses a range of options, including bioenergy with CCS (BECCS), direct air capture (DAC), and natural climate solutions (e.g., afforestation/reforestation, soil carbon sequestration). Most models represent this policy as a national cap-and-trade policy across the economy.[3] Models that do not represent mitigation opportunities explicitly from land use, land use

[1] Model intercomparisons can help to identify the robustness of results more formal uncertainty analyses, which are less frequently conducted or done with one model only [59]. Structural differences across models include the solution approach (Table 1), sectoral coverage and interactions, temporal resolution and extent, spatial resolution and extent, and degree of foresight.

[2] Most models assume linear caps from current levels, which are implemented as upper bounds on CO_2 emissions. However, some models have lower emissions than a linear trajectory for interim years, owing in part to expiring IRA tax credits. Banking and borrowing of emissions are not included.

[3] Revenues are recycled back to consumers via a lump-sum distribution for models capable of representing such transfers.

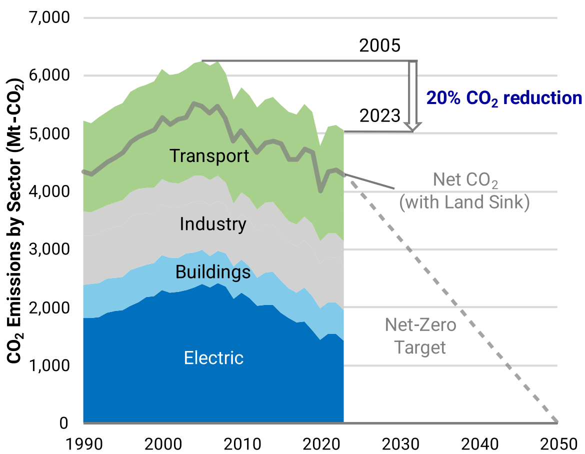

Fig. 1. Comparison of U.S. historical CO_2 emissions by sector and cap for the net-zero scenario. Historical emissions come from the U.S. Environmental Protection Agency's "Inventory of U.S. Greenhouse Gas Emissions and Sinks" and Rhodium data for 2023 [28,29]. Industry includes CO_2 from fossil fuel combustion and industrial processes.

change, and forestry (LULUCF) generally assume a constant sink of 800 million metric tons of CO_2 (Mt-CO_2) annually.[4] This land sink assumption is only used for models that do not represent land mitigation explicitly, and some factors may weaken the land sink relative to current levels (as suggested in the recent literature [26]) while others such as climate policy may lead to actions that enhance the land sink [27]. For models that include countries outside of the U.S., the scenario assumes that other countries face the same carbon price as the U.S. to minimize trade impacts. Although the net-zero target focuses on CO_2, the resulting shadow price from the emissions cap is applied to non-CO_2 GHG emissions for models that include other GHGs. The net-zero scenarios layer this economy-wide CO_2 reduction pathway on other reference scenario assumptions about state-level policies, markets, and technologies.

- **Net-Zero with IRA:** This scenario layers IRA and IIJA incentives on the net-zero scenario.

The scenario design also includes advanced technology scenarios that use the same policies as above but also more optimistic assumptions about decarbonization options across buildings, industry, transport, and carbon management. Figures in later sections typically show results across baseline and advanced technology scenarios. Results from additional study group scenarios are discussed in their respective papers [21,19,30,20].

See Browning, et al. (2023), including the supplemental material, for additional details about the EMF 37 study and scenario.

2.2. Models

The EMF 37 study includes a range of energy-economic models with different sectoral coverage, geographical scopes, solution concepts, technological detail, and temporal resolution. This paper includes the subset of EMF 37 models that submitted reference and economy-wide net-zero CO_2 scenarios (Table 1). Models responded to an open call to participate in the EMF 37 study, which is open to any North American economy-wide, energy system, or sectoral model. The 14 participating models represent prominent energy-economic models for the U.S. and have been featured in several recent policy analyses, including IRA's energy provisions [17] and EPA's power plant rules [31]. The EMF 37 study also includes sectoral models, which are highlighted in sector-specific papers on transportation and electricity [19,18]. Table S1 provides additional information about model coverage, and compares technological detail across participating models. Most participating models in the EMF 37 study are national energy-economic models as opposed to global integrated assessment models (IAMs). IAMs typically represent integrated energy-economy-land-climate systems, which typically have greater geographical coverage and climate interactions than national energy-economic models but less technological, sectoral, and spatiotemporal detail [32]. These latter characteristics are

Table 1
Models included in this analysis and key features. See for additional detail on coverage and for technological detail. CGE, computable general equilibrium; IAM, integrated assessment model; LP, linear program; QP, quadratic program. Models that submitted IRA incentives are designated with an asterisk.

Abbreviation	Model(s)	Analysis Institution	Coverage and Approach	Link
ADAGE	Applied Dynamic Analysis of the Global Economy	RTI International	Economy: CGE	Link
AnyMOD	AnyModel	Technische Universität Berlin	Economy: Least-cost LP	Link
EC-MSMR	Multi-Sector, Multi-Region	Environment and Climate Change Canada	Economy: CGE	Link
EPA-TIMES	The Integrated MARKAL-EFOM System	U.S. Environmental Protection Agency (EPA)	Economy: Least-cost LP	Link
EPS*	Energy Policy Simulator	Energy Innovation	Economy: System dynamics + logit choice	Link
FARM*	Future Agricultural Resources Model	USDA Economic Research Service	Economy: CGE	Link
FECM-NEMS*	National Energy Modeling System (with enhancements)	OnLocation, Inc. (funded by DOE Office of Fossil Energy and Carbon Management)	Economy: Multiple modules with least-cost LP supply and consumer adoption demand	Link
GCAM*	Global Change Analysis Model	Joint Global Change Research Institute	Economy (and other IAM systems): Logit choice	Link
GCAM-USA	Global Change Analysis Model for USA	Joint Global Change Research Institute	Economy (and other IAM systems): Logit choice	Link
gTech	gTech	Navius Research	Economy: CGE	Link
NATEM	North American Times Energy Model	Esmia Consultants	Economy: Least-cost LP	Link
TEMOA	Tools for Energy Model Optimization and Analysis	North Carolina State University	Economy: Least-cost LP	Link
US-REGEN	U.S. Regional Economy, Greenhouse Gas, and Energy	Electric Power Research Institute (EPRI)	Energy end use: Lagged logit choice; Power: Least-cost LP	Link
USREP-ReEDS*	U.S. Regional Energy Policy (economy); Regional Energy Deployment System (power sector)	Massachusetts Institute of Technology (MIT); NREL	Economy: CGE; Power: Least-cost LP	Link

[4] This land sink assumption is based on historical sequestration values published by the U.S. Environmental Protection Agency (EPA) "Inventory of U.S. Greenhouse Gas Emissions and Sinks."

important for representing net-zero energy systems, which are the focus of this paper [13].

2.3. Caveats

There are several caveats to consider when interpreting outputs:

- The goal of this modeling is to generate insights, and not to produce precise numbers [33,34]. Results should not be interpreted as predictions or forecasts.
- Although modeling teams ran coordinated scenarios, several assumptions remain unharmonized across models, including technological costs and fuel prices. Modelers were encouraged to calibrate reference scenario service demand assumptions and fuel prices to the U.S. Energy Information Administration's *Annual Energy Outlook 2022*, where possible.[5] These EIA assumptions are used for projections for demographics (e.g., population), service demand (e.g., vehicle miles traveled), and economic activity (e.g., GDP) to provide cross-model consistency in the reference scenario (i.e., to control for variation in the assumed extent of socioeconomic growth).[6] A recent IRA multi-model study [35] compared input assumptions for electric sector capital costs across several U.S. models, including many in Table 1, and found that most models use assumptions from the National Renewable Energy Laboratory (NREL) *Annual Technology Baseline*.
- These scenarios do not reflect recent developments since 2022, including changes in data center load projections, interest rates, post-pandemic economic growth, as well as federal and state policy changes, including finalized EPA regulations (e.g., related to vehicles, power plants) [36].
- Models vary in how they represent low-carbon technologies and conversion pathways. Individual study groups and cross-cut papers from EMF 37 offer more detailed discussions of model representations and how alternative representations can affect the results coming out of the models [21,19,30,20,24,22,23,18].
- Only 5 of the 14 models in Table 1 submitted runs with IRA incentives.[7] For comparability, the results section presents figures showing scenarios with and without IRA incentives separately.
- Net-zero scenarios in this paper focus on reaching net-zero CO_2 by 2050. Additional scenarios in the EMF 37 study look at other net-zero timeframes and net-zero GHG emissions (though not all participating models include non-CO_2 GHGs).
- Regional differences may be important for understanding national trends but were not systematically investigated here.

3. Results

3.1. Emissions

For net-zero pathways, models agree that electricity plays a central role in decarbonization efforts through direct CO_2 reductions from electricity generation and indirect mitigation in other sectors through electrification and, to a lesser extent, substitution of electricity-derived fuels for fossil fuels in uses where direct electrification is more challenging or costly (Fig. 2 and Fig. 7). Despite significant growth in electricity demand (Fig. 8), power sector CO_2 declines by over 80 % by 2050 from 2020 levels for most models under net-zero policies.

In net-zero scenarios, the transport and power sectors account for significant shares of emissions reductions, yet reductions are needed across all sectors in the models. There is larger variation across models in the pace and extent of direct CO_2 reductions in the buildings and industrial sectors. Individual sectors do not necessarily have to achieve net-zero emissions to reach the economy-wide target if negative emissions options are available. At deeper decarbonization levels, marginal abatement costs may exceed CDR costs in some sectors. This could render it more cost-effective to maintain positive residual emissions that are balanced by CDR, especially for costly to abate applications (e.g., challenging to electrify transport markets such as aviation and maritime, energy-intensive manufacturing such as iron and steel, production of fuels and chemicals). Industry generally has the highest residual CO_2 emissions in 2050 under net-zero and reference scenarios due to its higher abatement costs and service demand growth relative to other sectors [20]. Under reference conditions, transport exhibits the largest reductions from current levels due to the cost-competitiveness of vehicle electrification and fuel economy improvements, even without net-zero policies [19]. Model-specific sectoral emissions reductions are shown in Figure S4.

In net-zero scenarios, there is significant cross-model variation in residual emissions by sector and in the composition of the negative emissions portfolio across land use, BECCS, and DAC. Residual emissions under net-zero policy range from 800–3000 Mt-CO_2/yr across models in 2050 (Fig. 3). All U.S. models have contributions from land use, at levels that are generally greater than many countries where LULUCF may be a net source of emissions instead of a net sink [13].

In 2035, sectoral gaps in emissions projections between current policies and net-zero pathways occur predominantly in the power sector (Fig. 4), which reflects the lower marginal costs of abatement for electricity for near-term emissions reductions [37,18,38]. IRA incentives partially address this near-term gap [17]. By 2050, residual CO_2 in net-zero scenarios is highest for industry and transport (e.g., difficult to electrify segments) for many models. Residual emissions also occur for applications with slower stock turnover. There is a significant long-term gap in CDR deployment, as technological CDR is minimal by 2050 with current policies (Fig. 3).

The recent U.S. Biennial Transparency Report (BTR) contains updated modeling and scenarios to track progress relative to Paris Agreement targets, including recent regulatory changes, updated IRA representations, and cross-sensitivities on technology and fuel cost assumptions. Appendix 3 compares energy-related CO_2 projections between the BTR and EMF 37 scenarios. Although BTR scenarios span a wide range of post-2035 emissions, these scenarios are consistent with EMF 37 IRA results, especially in their significant reductions relative to current policy scenarios without IRA incentives.

Net-zero CO_2 policies also lead to large emissions reductions of other air pollutants, yielding air quality improvements. Economy-wide NO_x declines 54–70 % across models from 2020 levels with net-zero CO_2 policies (interquartile range), compared with 33–46 % with reference policies (Fig. 15). Similarly, economy-wide SO_2 emissions decline by 64–75 % from 2020 with net-zero policies (27–40 % interquartile range with reference policies). Anthropogenic emissions of NO_x and SO_2 are emitted predominantly through combustion processes. Thus, residual combustion in net-zero scenarios limits additional emissions reductions. Nevertheless, the remaining criteria pollutant emissions also indicate that additional policies, actions, and incentives may need to be in place to lower emissions further [24,39].

3.2. Energy system impacts

Net-zero policies amplify preexisting trends of electricity decarbonization, energy efficiency, and electrification but can lead to large increases in CCS deployment from historical trends and from reference scenarios (Fig. 5). There is general agreement across models on these key

[5] Following standard EMF practice, modeling teams who have developed their own projections are encouraged to use them, since external projections are dependent on many economic, technology, and behavioral assumptions.

[6] Some participating models have endogenous feedbacks in policy scenarios that may alter these trajectories (especially the computable general equilibrium models in Table S1]).

[7] For models that submitted IRA results, there may be other updates included relative to the reference scenario without IRA.

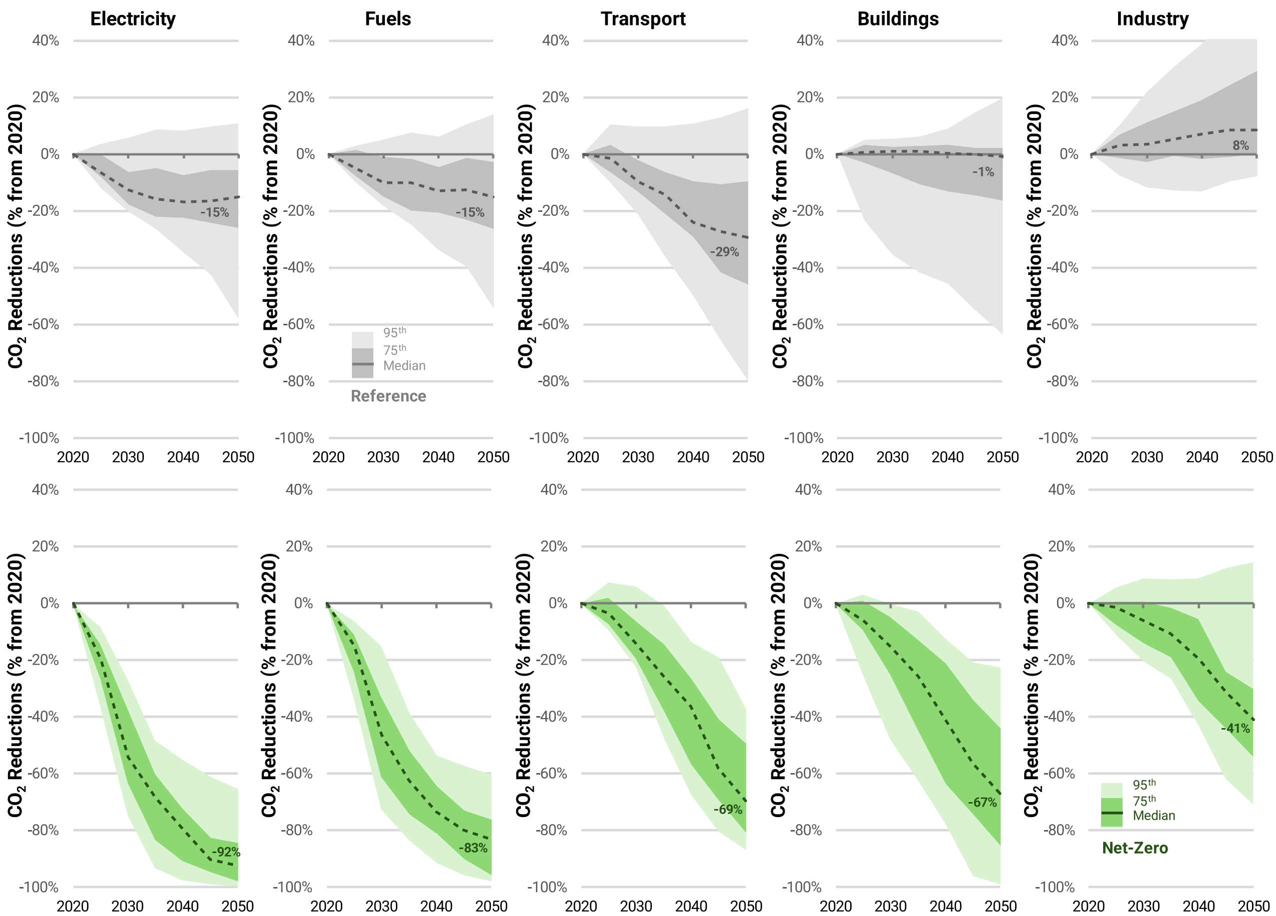

Fig. 2. Cross-model comparison of sectoral emissions under reference scenarios (top row) and net-zero policies (bottom row). Sectoral emissions are indexed to 2020 levels and show energy-related CO_2 emissions. Panels show ranges across models for the 5th to 95th percentiles (lighter area), 25th to 75th percentiles (darker area), and median (dashed line). Panels include scenarios with baseline and advanced technology assumptions for the economy-wide models in Table 1 and show scenarios without IRA incentives. "Fuels" includes all non-electric fuels supply and conversion emissions.

elements of decarbonization projections, but there are large differences in magnitudes that drive differences in residual emissions and CDR demand (Fig. 4). Models also agree that IRA's climate provisions impact near-term outcomes most, especially under current policies. IRA has smaller effects on longer-term outcomes relative to net-zero policies. IRA impacts are largest for accelerating power sector CO_2 declines, which is consistent with the results from a recent IRA multi-model study [35]. However, generalizations are challenging due to the small number of models with IRA cases (5 of 14 models).

While net-zero policies may lower fossil fuel consumption, achieving net-zero emissions does not necessarily phase out all fossil fuels (Fig. 6). Under reference conditions, models largely agree that coal will continue its historical decline, though there is variation in extent across models.[8] Models also agree that petroleum consumption is expected to decline, although there is large uncertainty about how much will be displaced via transport electrification. Models generally indicate increases in natural gas consumption over time; however, magnitudes can be lower with higher fuel prices or higher IRA credit uptake.

Under net-zero policies, declining demand for coal and petroleum is accelerated. Models agree that coal use declines fastest owing to its high-carbon intensity and relative ease of substitution in the power sector, which lead to declines of over 70 % from 2020 across the economy by 2035. Decreases in petroleum use roughly double by 2050 compared with reference levels, but there is still considerable consumption in many models. Natural gas shows a fundamentally different dynamic between the scenarios, as it generally grows in the reference but shrinks with net-zero policies, though this decline is modest relative to other fuels. Some models exhibit increases in natural gas consumption as systems approach net-zero CO_2 levels due to deployment of CCS-equipped gas generation in the power sector as unabated gas generation declines and due to DAC deployment based on high-temperature liquid solvent configurations, where natural gas may be used for heating requirements.[9] Pipeline gas composition varies by model, as does the sectoral allocation across power, industry, and buildings (Fig. 7). Note that the role of fossil fuels across scenarios depends on the availability and cost of CDR and CCS. Limited availability of these options could lower fossil fuel consumption further, albeit with higher costs, as shown in the EMF 37 carbon management scenarios without CCS [21].

Fossil fuel production in the U.S. exhibits similar trends as

[8] Coal declines could be faster under reference policies if EPA's power plant greenhouse gas standards were included.

[9] For models that include non-CO_2 GHGs, upstream methane emissions associated with natural gas are penalized based on the carbon price in a given period (Figure 11), which could encourage abatement of these non-combustion emissions and fuel switching.

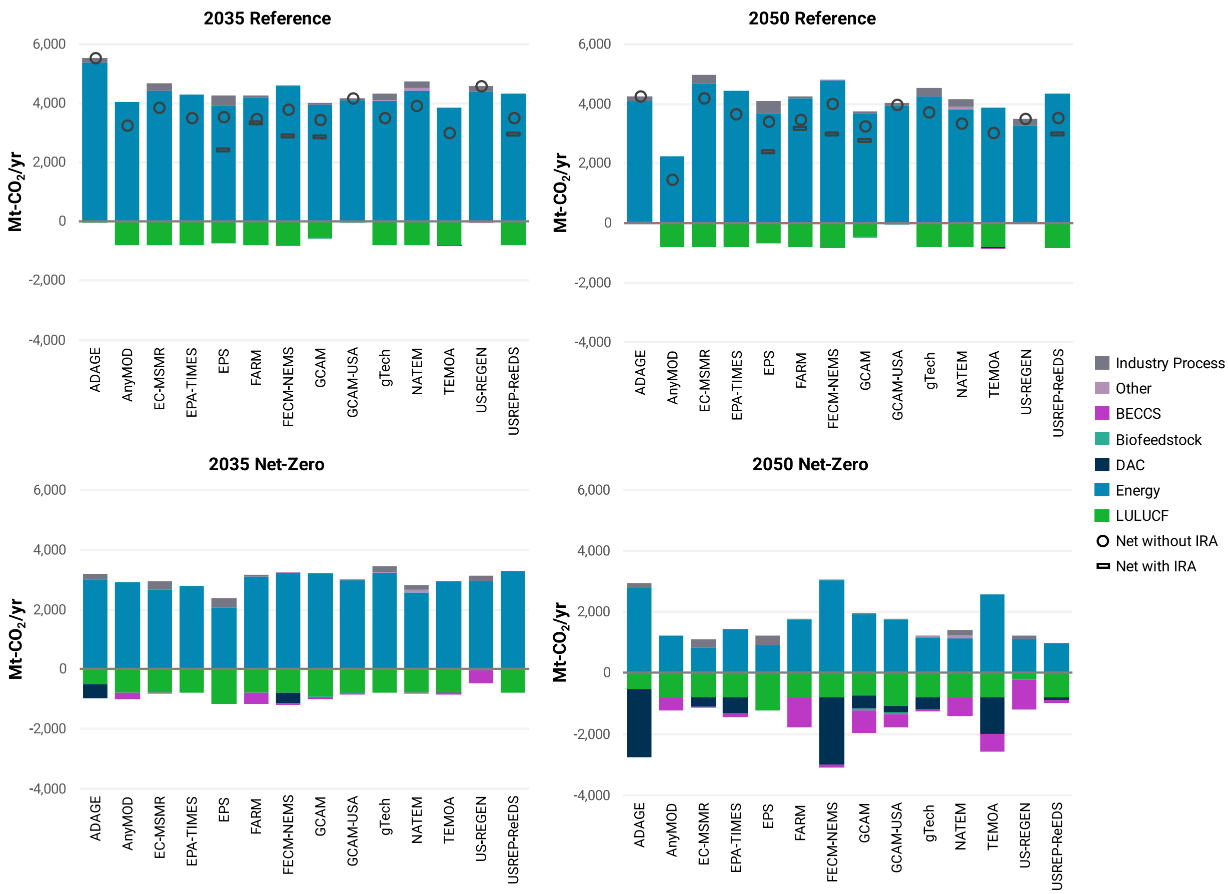

Fig. 3. CO_2 emissions decomposition by model, year, and scenario. Values are shown for 2035 and 2050 (left and right columns, respectively) under reference and net-zero scenarios (top and bottom rows, respectively). Net emissions under reference scenarios with Inflation Reduction Act tax credits are shown as dashes, and scenarios without IRA are shown as circles. Many models use an exogenous land sink assumption (−800 Mt-CO_2/yr), while others represent endogenous land sink emissions. BECCS = bioenergy with carbon capture and sequestration; DAC = direct air capture; IRA = Inflation Reduction Act; LULUCF = land use, land use change, and forestry.

consumption. Production volumes ultimately depend not only on domestic consumption but also on exports and imports.[10]

Models indicate higher electrification rates (i.e., electricity's share of final energy) under net-zero policies in all sectors; however, there are sector-specific trends in fuel use and cross-model variation (Fig. 7).

- **Transport:** Despite electrification trends, models still project large petroleum consumption for transportation, especially for costly to electrify segments (e.g., aviation, international shipping and other maritime, long-haul trucking). Most models significantly increase biofuel consumption under net-zero scenarios, especially for transportation modes that are difficult to electrify, but there is broad variation in biofuel use across models. Hydrogen is used in a few models for transport.
- **Industry:** The industrial sector exhibits the greatest variety of fuels and variation across models. Industrial decarbonization entails significant heterogeneity across subsectors and applications, which creates modeling challenges [20], and is generally viewed as more costly to abate relative to other sectors with fewer mitigation options, which is reflected in Fig. 1. Models exhibit variation in industrial electrification potential and the degree of low-carbon fuel use (e.g., hydrogen, biomass).
- **Buildings:** Residential and commercial buildings already have high electricity shares today (50 % nationally), and electrification is the main pathway for additional emissions reductions, though models also suggest gas use remains even with net-zero targets due to slower stock turnover.

End-use electrification leads to electricity demand growing faster than it has over the last two decades but well within experience from longer-run rates (Fig. 8). There is higher electricity demand growth over time with net-zero policies, but growth exceeds the recent pace even with current policies through 2035. However, there is significant disagreement across models in the extent of power sector growth [18], which reflects uncertainties about reference trends, the degree of electrification, offsetting efficiency, electrolytic hydrogen demand, and direct air capture in some models.

3.3. Power sector impacts

Model results underscore the key role of the power sector in decarbonization pathways, with agreement about some trends (e.g., solar and wind representing the majority of new capacity, much lower coal generation), and uncertainty about others (e.g., degree of energy storage deployment, extent of gas-fired generation). As shown in Fig. 9, wind and solar increase over time in reference and net-zero scenarios with large cross-model variation, especially in 2050 that partially reflects

[10] Scenarios assume that non-U.S. countries adopt similarly stringent climate policy to the U.S., though most participating models only represent the U.S. and make exogenous assumptions about foreign demand. Lower policy ambition in other countries may mean higher exports and production under U.S. net-zero scenarios. This creates the potential for generating additional government revenues if the net-zero policy is implemented via carbon pricing [59].

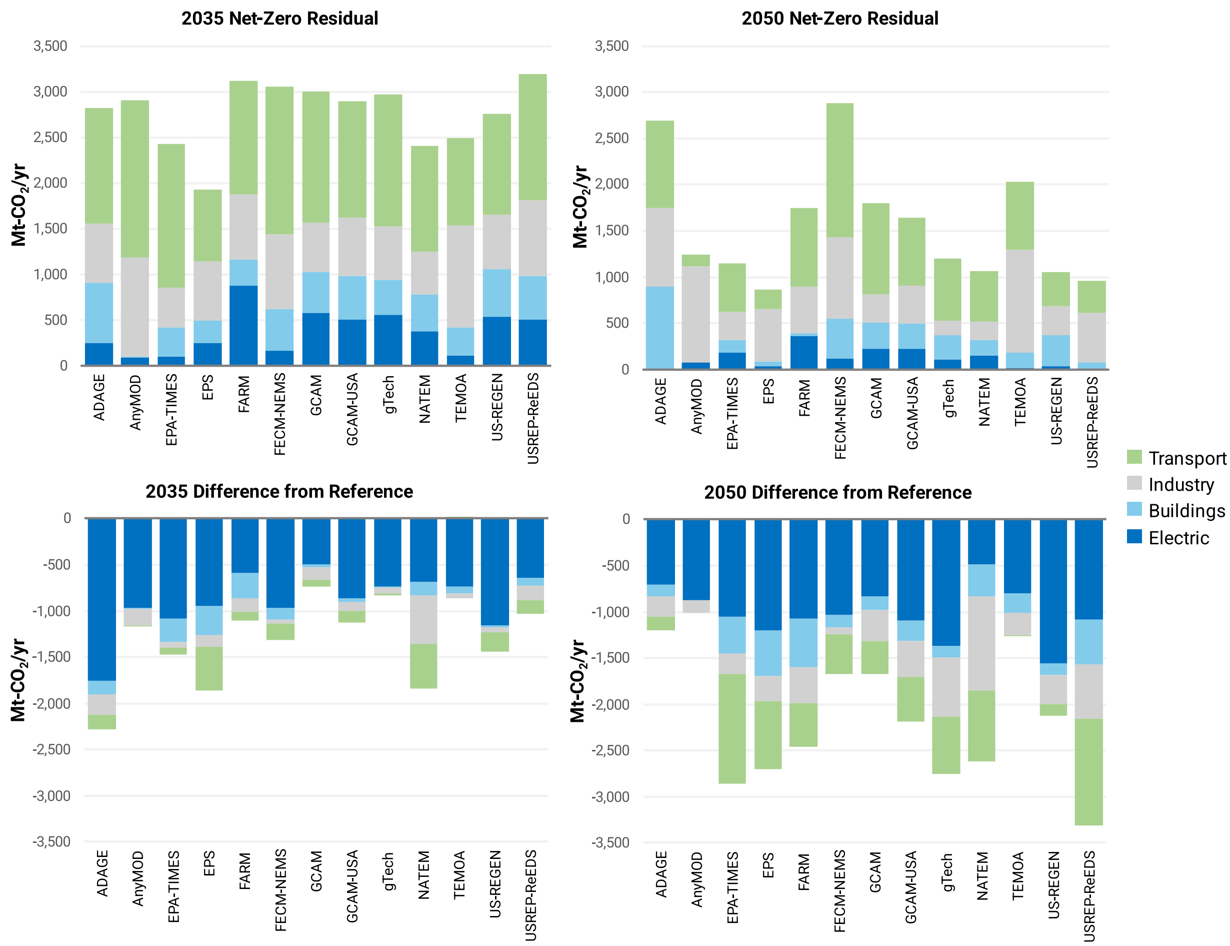

Fig. 4. Residual CO_2 by sector (top row) and difference between net-zero and reference scenarios (bottom row). Values are shown for 2035 and 2050 (left and right columns, respectively).

differences in electricity demand (Fig. 8). Many models see an important role for natural gas, even with net-zero policies, where generation falls faster than capacity (i.e., lower capacity factors over time [40,41,4]).

Solar and wind capacity additions greatly exceed historical levels to reach net-zero emissions, which comprise 60–96 % of new capacity across models (Fig. 10). Generation and energy storage capacity additions expand dramatically with net-zero policy compared with the reference, though IRA is projected to increase wind, solar, and energy storage additions [35]. Models vary in their extent of low-carbon firm[12] technology deployment, including CCS, nuclear, and long-duration energy storage.

These model results suggest that abundant clean electricity is a centerpiece of decarbonization with accelerated deployment across all scenarios. These projected dynamics may raise questions about the ability to site and permit new resources and supporting infrastructure, overcome local concerns, maintain resource adequacy and reliability, and manage interconnection processes [43–46].

[11] Electric technologies typically have much higher efficiencies in terms of final energy use per unit of service demand than fossil-fueled options (i.e., one joule of electricity displaces more than one joule of oil or natural gas), so service demand shares generally exceed final energy ones.

[12] Firm resources are "technologies that can be counted on to meet demand when needed in all seasons and over long durations (e.g., weeks or longer)" [42].

3.4. Economic impacts

For net-zero scenarios, marginal abatement costs per ton of CO_2 reduced varies across models, scenarios, and time (Fig. 11). Since most models implement net-zero policies through economy-wide CO_2 constraints, the carbon prices in Fig. 11 are shadow prices on these constraints. Carbon prices depend on the equilibrium mix of abatement options to meet the CO_2 goal and are contingent on model structure and input assumptions, which is reflected in lower prices with advanced technologies in Fig. 11. Marginal abatement costs tend to increase steeply as net-zero CO_2 emissions are approached. However, there is considerable cross-model variation in carbon prices to meet net-zero CO_2 in 2050, which indicates differences in the costs of emissions reductions and carbon removal technologies.

Stringent climate policy can have large fiscal impacts on tax revenue and government spending (Fig. 12). Fig. 12 compares revenue and subsidy magnitudes[13] across models for net-zero scenarios. If net-zero

[13] See Appendix 1.1 for details on these calculations. Policy revenues are the product of carbon prices and residual (gross) CO_2 emissions. Since most models implement net-zero policies through an economy-wide CO_2 constraint, carbon prices are shadow prices on this constraint over time, and CDR subsidies are payments to net sequestration based on the carbon price. Under this implementation, carbon prices apply symmetrically as a penalty on CO_2 and per-ton subsidy to negative emissions technologies. Subsidies illustrate public expenditures by category, which supplement private investments. Tax revenues and public expenditure impacts for the government would be more limited if permits are freely distributed instead of auctioned.

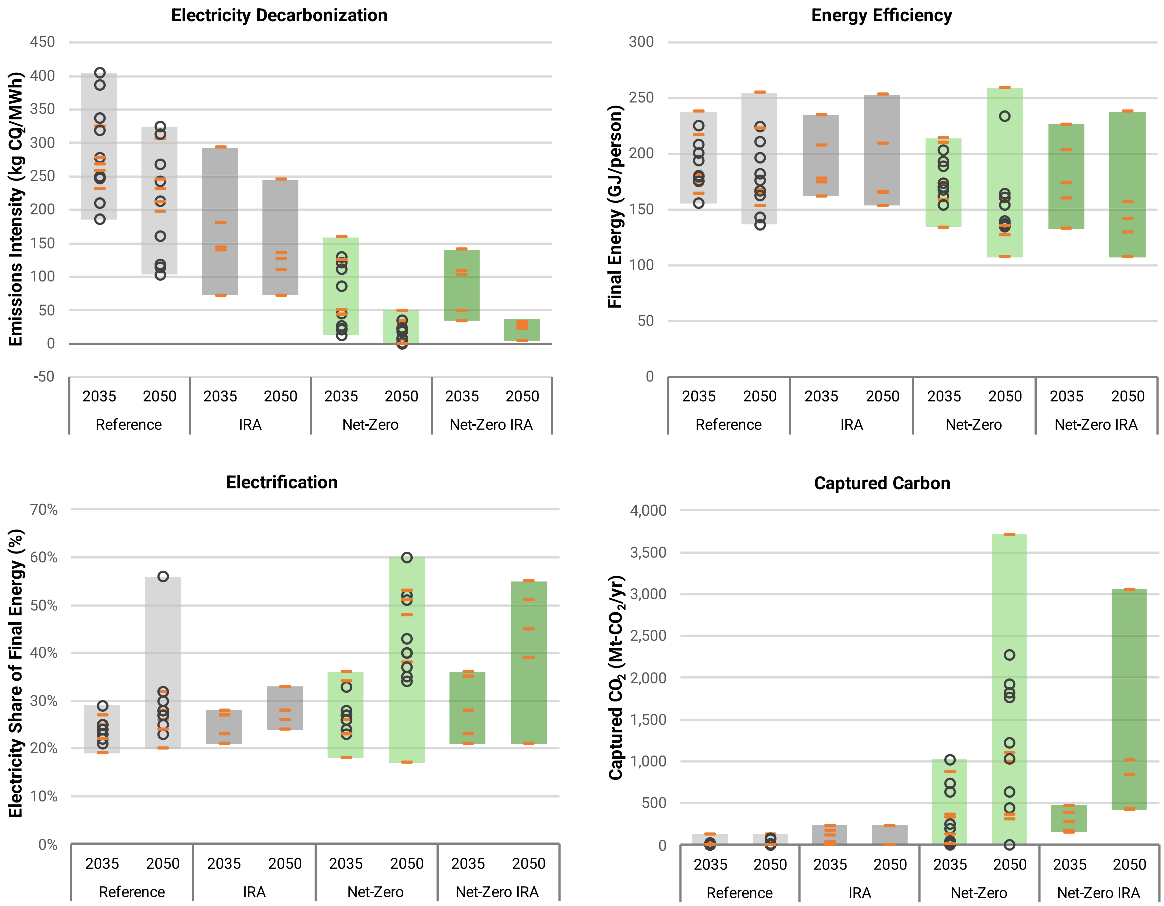

Fig. 5. Cross-model comparison of decarbonization pillars across scenarios in 2035 and 2050. Panels show emissions intensity of electricity (kg-CO_2/MWh, upper left), per-capita final energy (GJ per person), electricity share of final energy (%), and captured carbon (Mt-CO_2/yr). Models submitting IRA scenarios are shown in orange dashes, and other models are shown in black circles.

policy is implemented as a cap with auctioned permits or carbon fee, CO_2 permit revenue could be $110–1700 billion per year in 2050 across models (about $300–4400 per capita annually), which is about 0.2–3.7 % of GDP in 2050. Note that total U.S. tax revenue was 12.2 % of GDP in 2022 [47]. Net revenues to the government—after subtracting CDR subsidies—approach zero as emissions go to net-zero levels in most models.[14] Revenues are lower over time due to a declining tax base and payments to carbon removal but are partially offset by higher carbon prices in these models. Navigating dynamics of net revenues that peak and eventually fall to zero as emissions decline may present a fiscal management challenge for governments in climate policy design.

Model results indicate that expenditures on carbon removal could span 0.1–3.6 % of GDP annually by 2050. For context, Medicare outlays were 3.1 % of U.S. GDP in 2023 [48], and the Manhattan Project and Project Apollo both reached 0.4 % of U.S. GDP in their peak funding years [49]. These expenditures give an indication of the size of the carbon management industry under deep decarbonization scenarios. If net-zero policy is implemented as a carbon fee or cap-and-trade with auctioned permits, CDR payments with net-zero policies are generally higher than peak IRA subsidy levels, even if IRA provisions are extended to 2050.

Overall, these comparisons highlight how climate change mitigation is not only characterized by technological and economic opportunities and challenges but also fiscal ones. Although Fig. 12 focuses on national fiscal impacts, net-zero policy scenarios also imply substantial transfers across regions, because there is regional heterogeneity in mitigation costs, resource endowments, sectoral emissions, and CDR potential [50]. Additionally, the net-zero scenario assumption of policy implementation via a cost-minimizing economy-wide CO_2 cap could mean that impacts for public finance could be larger for other policies than Fig. 12 suggests [51].

Energy spending across the economy decreases relative to today for many models under reference and net-zero policies, especially as a share of GDP (Fig. 13). Energy spending in 2022 on an inflation-adjusted basis was over 20 % higher than 2021 and one of the highest years since 1970 largely due to higher petroleum prices, which have since fallen. The total annual costs of delivered fuels[15] decreases over time for many models with reference policies, since transport electrification decreases petroleum spending, even though electricity spending increases (electric vehicles are about three to four times more efficient than internal combustion vehicles [52]). Electrification could not only lower average energy costs for households and businesses but also potentially reduce year-to-year variability, since historical variation is largely due to petroleum price fluctuations. Net-zero policies increase energy spending

[14] The exceptions are models where CDR comes primarily from land use (Figure 3), since land sink payments are linked to incremental sequestration relative to the reference scenario. Note that inverted U-shaped curves of net revenues as stringency increases (i.e., carbon Laffer curves) can diminish progressive effects of climate policies [59].

[15] Only five models provided price reporting to calculate energy expenditures across scenarios.

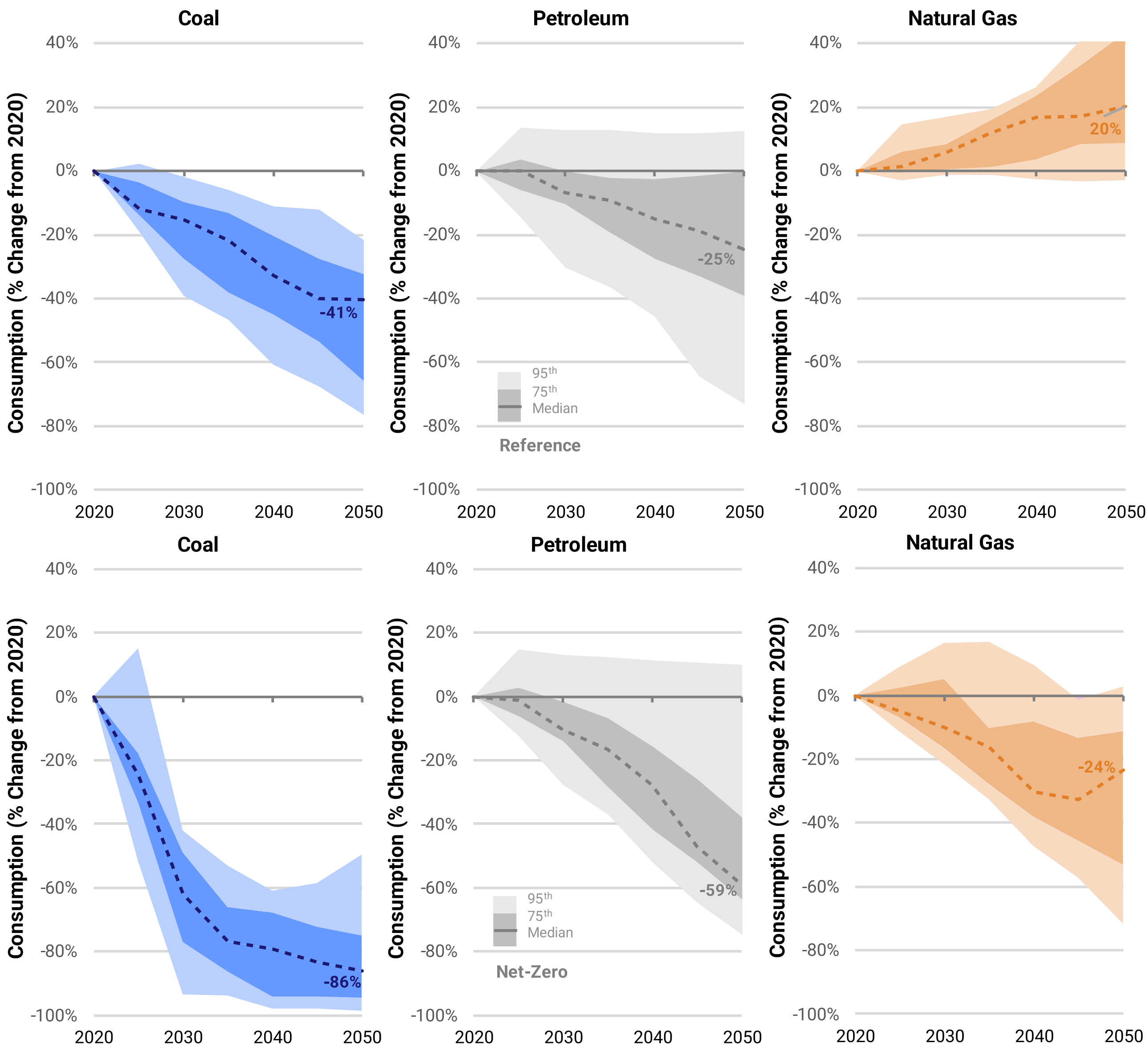

Fig. 6. Fossil fuel consumption over time by fuel and scenario under reference scenarios (top row) and net-zero policies (bottom row). Panels show ranges across models for the 5th to 95th percentiles (lighter area), 25th to 75th percentiles (darker area), and median (dashed line). Panels include scenarios with baseline and advanced technology assumptions for the economy-wide models in Table 1 and show scenarios without IRA incentives. Values are normalized to 2020 levels.

for most models relative to the reference scenario in part due to carbon pricing raising costs of delivered fuels, though the extent varies by model due to differences in the magnitude of the carbon price, where higher-cost CDR increases household energy costs (Fig. 11).[16] However, even with net-zero policies, delivered energy spending declines over time as a share of GDP across all models.

3.5. Policy efficacy

To understand the efficacy of net-zero policies across models, we calculate the semi-elasticity of CO_2 emissions with respect to the carbon price level. These values can be easily estimated for policy scenarios using model outputs (percentage decrease in emissions per dollar change in carbon price under the net-zero scenario relative to the reference)[17] and enable comparisons with empirical studies of carbon pricing. Higher values indicate more emissions reduction for each U.S. dollar of carbon price, which is the marginal cost of an additional ton of reduction to meet the economy-wide CO_2 constraint for scenarios in this study. These metrics reflect both policy stringency and design as well as model structures and input assumptions.

Policy semi-elasticities vary across models but are generally between 0.06 % to 0.31 % for all but one model[18] (Fig. 14). In other words, each U.S. dollar per metric ton carbon price leads to a 0.06 % to 0.31 % reduction in economy-wide CO_2 emissions. Higher policy efficacy

[16] High carbon prices could lead to tax carve-outs for sectors like retail gasoline to avoid energy price increases that could drive public opposition [45]. Note that EPS implements net-zero policies with standards and subsidies rather than carbon pricing, which leads to lower fuel costs relative to the reference scenario. Fewer models provided expenditure-related variables for the comparisons in this figure.

[17] See Appendix 1.4 for detail on these calculations. Semi-elasticities are useful in empirical contexts to allow unpriced emissions to remain in the regression with logarithmic transformations [46].

[18] EC-MSMR has a semi-elasticity of 0.74 %.

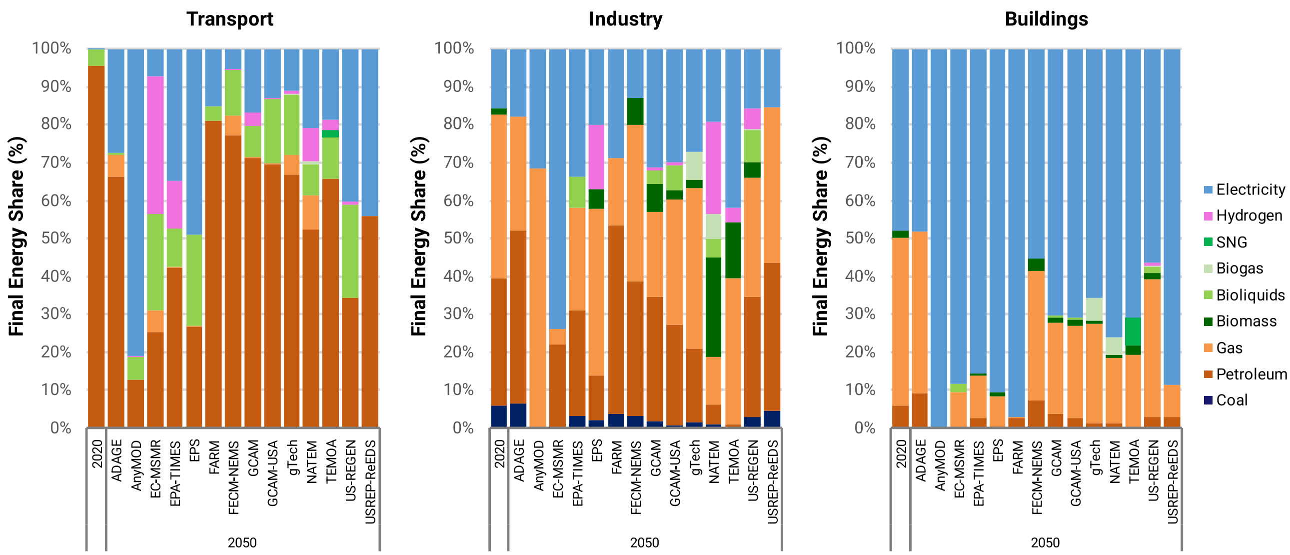

Fig. 7. Final energy by fuel, model, and sector. Sector panels show 2020 values (left bar) and cross-model projections with economy-wide net-zero CO_2 policy in 2050 (right bars).[11].

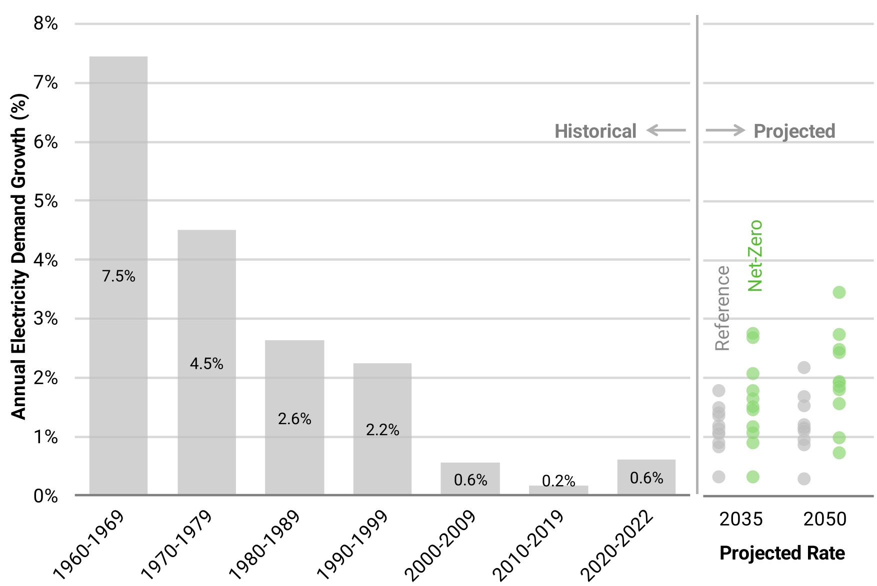

Fig. 8. Growth rates for electricity demand across models. Historical and projected values are compound annual growth rates. Projections show rates by model through 2035 and 2050 under reference and net-zero scenarios from 2020 levels. Panels include scenarios with baseline and advanced technology assumptions for the economy-wide models in Table 1 and show scenarios without IRA incentives. Historical values come from the U.S. Energy Information Administration's State Energy Data System (SEDS).

relates to lower carbon prices needed to reach the net-zero CO_2 targets, which varies across models due to differences in the costs of sectoral mitigation, availability and cost of CDR, and mix of deployed options, as discussed in Browning, et al. (2023).

The implied policy efficacy from EMF 37 scenarios generally aligns with ex-post empirical studies of carbon pricing (0.10 % to 0.51 %). The values from this study differ from empirical values both because these scenarios assume considerably more stringent targets than empirical values (all else equal, this assumption would lower semi-elasticities in this study) and because these scenarios generally assume cost-minimizing CO_2 caps as the climate policy instrument[19] (all else equal, this assumption would increase semi-elasticities here). Carbon policy semi-elasticities are lower for EMF 37 net-zero scenarios compared with IPCC AR6 scenarios, which could reflect differences in marginal abatement costs between national energy-economic models and global integrated assessment models as well as declining mitigation costs [13].[20] Figure S9 shows how policy semi-elasticities generally decline with greater decarbonization over time, which reflects convex marginal abatement cost curves [59].

4. Policy takeaways from EMF 37 study group papers

There are several EMF 37 papers that provide deep dives on cross-

[19] Many models are also not capturing the costs of raising revenue, revenue use, or macroeconomic feedbacks.

[20] Note that other cost- and welfare-related metrics such as GDP, consumption, and system costs are not reported by many models due in part to their scopes.

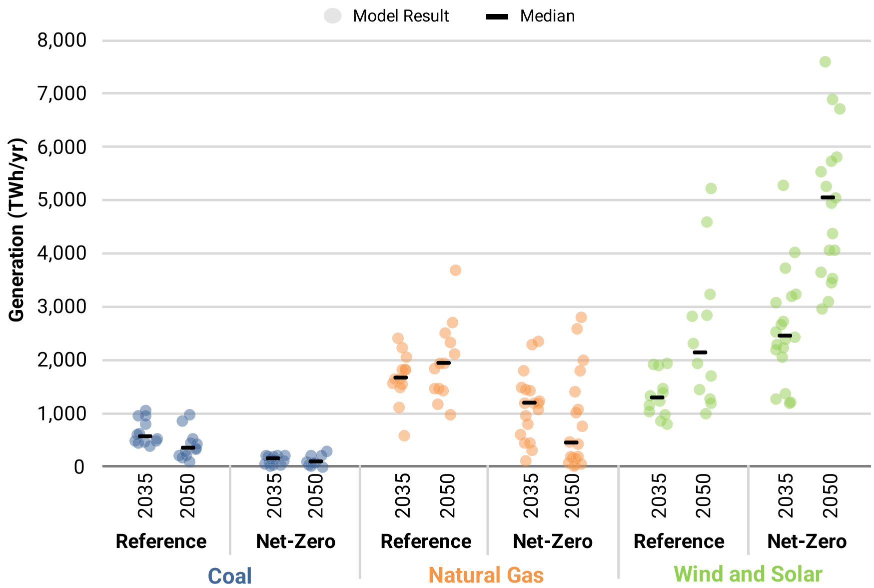

Fig. 9. Generation by model, grouped by technology, policy scenario, and time period. Individual model results are shown as dots with the median values across models as dashes. Panels include scenarios with baseline and advanced technology assumptions for the economy-wide models in Table 1 and show scenarios without IRA incentives. Generation shares are shown in Figure S7.

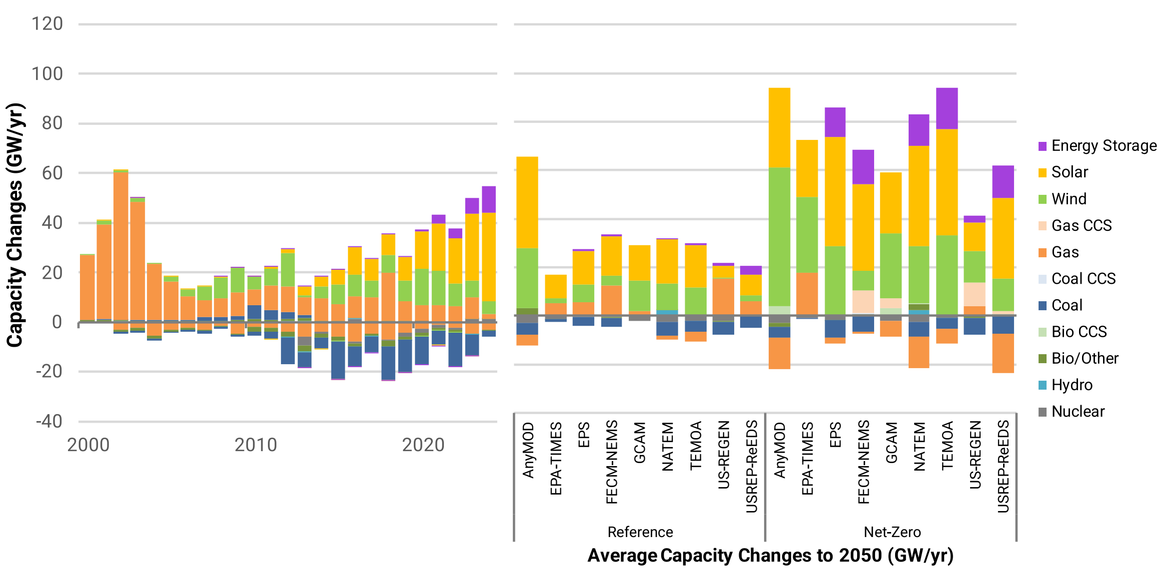

Fig. 10. Historical and projected net capacity additions and retirements by technology and model. Average annual changes through 2050 under the current policies reference and net-zero policy scenarios. Historical values come from EIA-860 data.

cutting issues and study group scenarios. This section provides high-level summaries of key takeaways from these papers along with references for readers who are interested in learning more. Policy takeaways from these studies include:

- **Electricity:** The electricity sector plays a central role in achieving net zero—it is often the fastest sector to decarbonize, and electricity demand growth rates accelerate to levels that the U.S. has not experienced in decades. The dual challenge of decarbonizing electricity production while meeting higher demand growth requires: 1. Unprecedented additions of wind, solar, and energy storage starting now and persisting through 2050; 2. Deployment of low-carbon firm technologies to replace the capacity contributions from existing fossil fuel-fired power plants and/or the widespread adoption of CDR to offset emissions from remaining fossil generation. Existing policies, including IRA incentives, EPA's finalized power plant rules, and state-level portfolio standards, are expected to move the power sector in this direction, but other barriers remain, including interconnection processes, siting and permitting, expanded transmission and other infrastructure, and rate design issues [18].
- **Transportation:** The transportation sector is often the largest source of emissions reductions in net-zero scenarios. Mitigation is driven by greater electrification of on-road vehicles (including extensive adoption with current policies in most models) and by the use of lower-emitting fuels for other travel modes, often biofuels, though models disagree on the degree of electrification and emissions

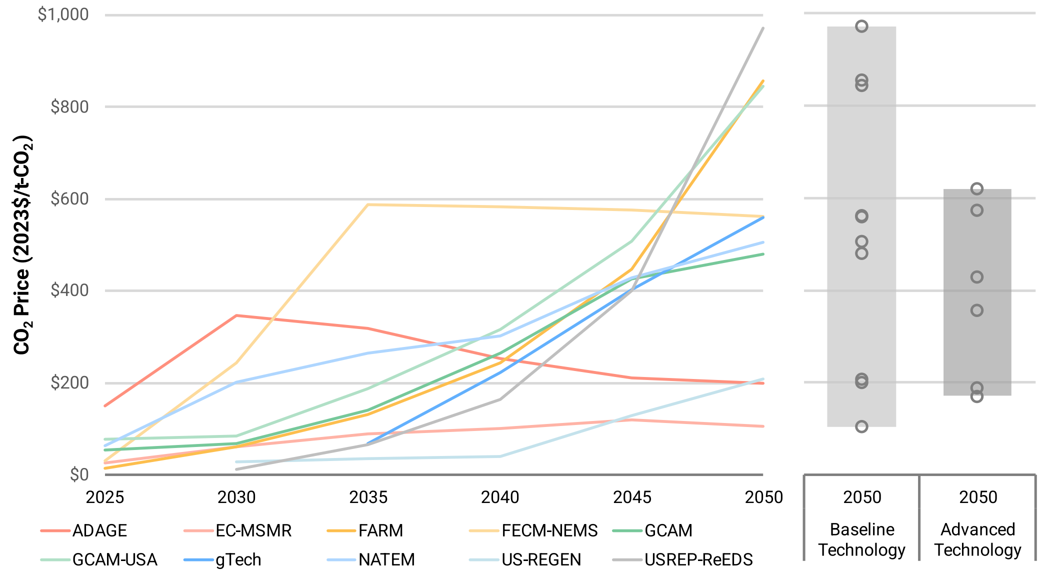

Fig. 11. CO_2 prices over time by model for net-zero scenarios. Values are shadow prices for economy-wide CO_2 cap constraints and are expressed in 2023 USD per metric ton of CO_2. The left panel shows the time trend with baseline technology assumptions, while the right panel compares 2050 prices across the baseline and advanced technology scenarios.

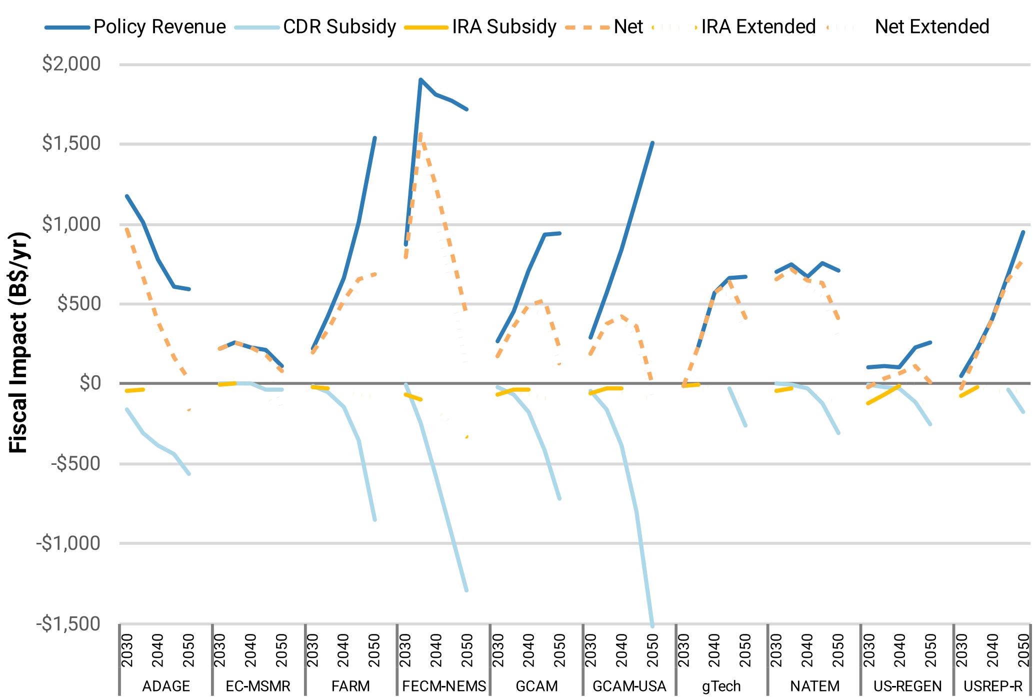

Fig. 12. Fiscal impacts over time by model under net-zero scenarios. Revenues show gross government revenues from CO_2 permits under net-zero policies. Carbon removal subsidies show implicit payments to CDR under net-zero CO_2 policies. Inflation Reduction Act subsidies are not explicitly reported but calculated based on deployment of IRA-subsidized resources in these scenarios. Details on calculations are provided in Appendix 1.1. CDR = carbon dioxide removal; IRA = Inflation Reduction Act. Values are shown in GDP terms in Figure S8.

reduction potential. The role of hydrogen for direct use in transport is consistently projected to be small, but its use in low-carbon fuel production can be large. Petroleum use declines by 30–70 % by 2050 in net-zero scenarios, though consumption remains due to limited alternatives for some travel modes and slow vehicle turnover. Existing policies, including IRA incentives, federal emissions standards, and state-level zero-emission vehicle targets, support electrification and production of low-emitting fuels. However, significant barriers remain to achieve major emissions reductions, including deploying charging infrastructure, leveraging vehicle-grid integration opportunities to reduce electricity costs and increase reliability, and scaling up low-carbon fuel production for aviation, shipping, and other applications [19].

- **Industry:** The main options for industrial decarbonization include energy efficiency, low-carbon fuels and feedstocks, industrial electrification, and CCUS. The applicability of each varies across individual industries, given the heterogeneity in applications, which suggests that there are no one-size-fits-all technology and policy solutions for industry. Modeling challenges for industry mean that care should be taken about drawing climate policy conclusions from

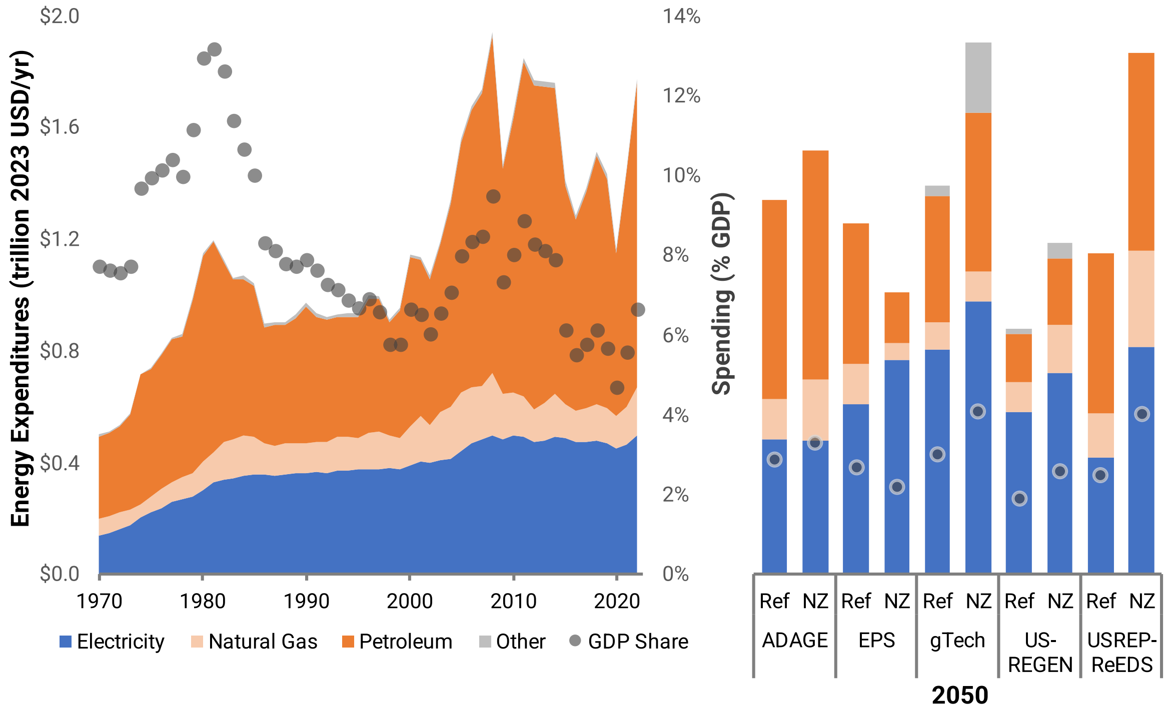

Fig. 13. Historical and projected economy-wide fuel expenditures across models and scenarios in 2050. Expenditures are shown in real 2023 USD terms (trillion $ per year) and as a share of GDP (secondary axis on both panels). Projections by model are shown for 2050 for reference and net-zero scenarios ("Ref" and "NZ," respectively). Fuel expenditures in the net-zero scenarios include carbon price except EPS, which implements net-zero CO_2 with standards and subsidies rather than carbon pricing.

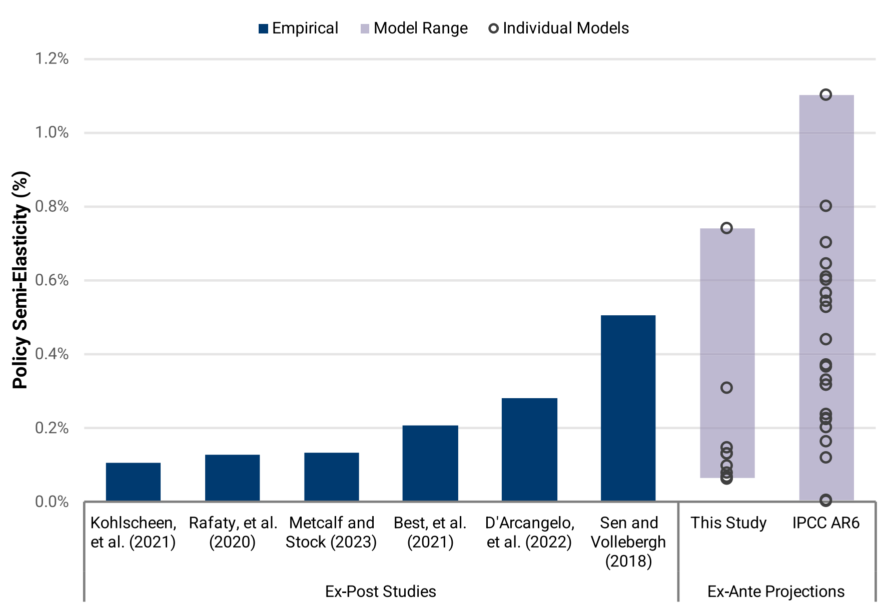

Fig. 14. Estimates of policy semi-elasticity of CO_2 emissions with respect to carbon prices. Semi-elasticities are the percentage change in emissions for each 2023 USD per metric ton CO_2 change in carbon price in 2050. Ex-post studies use observational data from a range of countries [53–58]. IPCC Sixth Assessment Report (AR6) scenario values come from Tol (2023). See Figure S9 for policy semi-elasticity values from EMF 37 models across different decarbonization levels.

current model results. On one hand, specific manufacturing sectors with large direct process emissions and high-temperature processes (e.g. cement, primary steel, basic bulk chemicals) only have a few or relatively expensive options to decarbonize, which would make it challenging to reach zero CO_2 emissions individually. On the other hand, results in current modeling may not fully reflect the range of industrial decarbonization pathways, especially as technologies evolve and studies examine individual decarbonization options for each industry [20].

- **Carbon management:** Carbon management technologies[21] are important elements of pathways to net-zero CO_2 emissions across many models and scenarios. Total capture rates of CO_2 (including fossil, bioenergy, and DAC) average 1.3 gigatons of CO_2 annually across all models in 2050 in the central net-zero scenario, which implies a substantial upscaling of capacity to move and store CO_2. BECCS and DAC rates range from 0–2.3 Gt-CO_2/year in 2050. Limited availability of CCS could lower fossil fuel consumption further, albeit with higher costs, as shown in the EMF 37 carbon management scenarios without CCS. For these scenarios that constrain CCS deployment, many models could not reach net-zero CO_2 by 2050. For models that can achieve net-zero CO_2 without CCS, decarbonization costs are significantly higher (marginal costs are 2–10 times higher than with CCS). The carbon price at which DAC was deployed at scale depended on the assumed cost, which ranged between $250 and $500 per metric ton CO_2 across models [21].
- **Hydrogen:** Hydrogen uptake varies significantly across models as does the representation of hydrogen technologies and markets, which makes policy recommendations challenging. Under net-zero policies, the highest uptake of hydrogen is in industry and transport; however, there are substitutes for hydrogen that may be lower cost for these applications such as electrification, bioenergy, and fossil fuels (either with CCS or CDR). Many scenarios report zero or near-zero hydrogen consumption, but the average demand across models reporting non-zero hydrogen consumption by 2050 is 10 MMT for transportation and 16 MMT for industry. The most significant demand subsectors are energy-intensive manufacturing and non-manufacturing for industry, as well as freight road (e.g., medium- and heavy-duty trucks) for transport, though some models report hydrogen use for synthetic fuels, electricity generation, and off-road transport [22].
- **Bioenergy:** Bioenergy consumption increases across net-zero scenarios (more than doubling by 2050 relative to 2020 levels on average, as shown in Figure S5), with the largest increases in electricity generation and transportation fuels. The primary driver for bioenergy in electricity generation is the contribution of BECCS toward carbon sequestration, providing net negative emissions to help meet economy-wide net-zero CO_2. Biomass competes with DAC and a forest sink for CDR from the atmosphere. Even with a transition from internal combustion to electric vehicles, the use of biofuels for transportation increases over time under net-zero policy scenarios. Further considerations for increasing demand for bioenergy include competition for agricultural land, the pace of electrification of ground transportation, and a declining forest land sink [23].
- **Air quality:** Achieving net-zero CO_2 has the potential to yield air quality improvements, since CO_2 and air pollutants are co-emitting during combustion. This response was explored by examining the air pollutant emission projections from EMF 37 modeling teams and further evaluated using a reduced-form air quality and health benefits model for a subset of models. Despite significant differences in model structure, the results suggest that achieving net-zero CO_2 will result in decreases in long-term air pollutant emissions, leading to widespread improvements in air quality and significant health benefits, ranging from $65 billion to $250 billion in 2035. Differences in projections across models reflect differences in sectoral coverage, coal-fired power plant retirements, fossil fuel use, and air pollutant emission factors, including the degree to which air quality regulations are considered. Multi-model analyses can help to assess these impacts and to design policies that maximize health benefits while avoiding unintended negative consequences on air quality, especially in vulnerable communities [24].
- **Comparison with Europe:** By analyzing over 28 integrated assessment and energy models, this paper identifies that, while both Europe and the U.S. can reach net zero by 2050, the U.S. may rely more on CCS technologies [60]. In contrast, Europe might emphasize electrification and renewable energy deployment to a greater extent. Industrial processes are highlighted as the most challenging to decarbonize in both regions. Despite differing policies and targets, both regions require similar carbon pricing to meet their goals. Policy-makers could address barriers to electrification in sectors like industry and transportation and consider the strategic role of technologies such as CCS.

5. Conclusions and research needs

This study investigates potential policy implications of reaching economy-wide net-zero CO_2 emissions across the U.S. by 2050 using results from the EMF 37 multi-model comparison. The analysis highlights technological and sectoral gaps in reaching net-zero relative to current policies and market trends. Model results indicate that net-zero policies amplify preexisting trends of electricity decarbonization, energy efficiency, and electrification but project large departures in higher CCS and CDR deployment, though there are important cross-model differences in the extent of these changes (Fig. 15). Net-zero CO_2 policies also could lead to large non-CO_2 emissions reductions and air quality improvements [24], though additional policies and incentives may need to be in place to target further air quality improvements. These comparisons also illustrate how stringent climate policy can have significant fiscal impacts on tax revenue and government spending. Spending on fuels across the economy decreases relative to today for many models under reference and net-zero policies, especially as a share of GDP, primarily due to the higher efficiency of end-use electrification. CO_2 tax revenue could be $110–1700 billion per year in 2050 across models, which is about 0.1–3.7 % of GDP, but net revenues to the government—after subtracting CDR subsidies—approach zero as emissions approach net-zero levels.

To support an economy-wide net-zero goal, these results indicate that not every sector and application needs to target net-zero emissions, though all sectors pursue deep emissions reductions. Some areas may target net-negative emissions via carbon removal while others would not likely reach net-zero levels if affordability and cost-effectiveness are prioritized. Reliance on CDR—by sector and in total—depends on its cost, which is uncertain and varies between models. A key challenge is that mitigation targets depend to some degree on the abatement and innovation outcomes in other sectors, especially for electricity decarbonization and deployment of carbon removal technologies.

For instance, modeling in EMF 37 shows that the industrial sector has the smallest reductions in net-zero scenarios (Fig. 2). However, the industrial sector is one of the hardest to model [20], and if industrial decarbonization pathways are less costly than indicated in current models, there may be less need for CDR options to offset residual emissions. This could have important fiscal and policy implications, given the large fiscal impact of CDR subsidies shown in Fig. 12. However, if RD&D are able to drive down the costs of industrial sector

[21] Carbon capture and sequestration (CCS) refers to technologies that capture CO_2 either from point sources, including power plants or industrial facilities (e.g., cement), or ambient air through direct air capture (DAC). A subset of CCS technologies provides carbon dioxide removal (CDR), which provides net removal of CO_2 from the atmosphere, including BECCS and DAC. Terrestrial carbon sequestration also provides CO_2 removals.

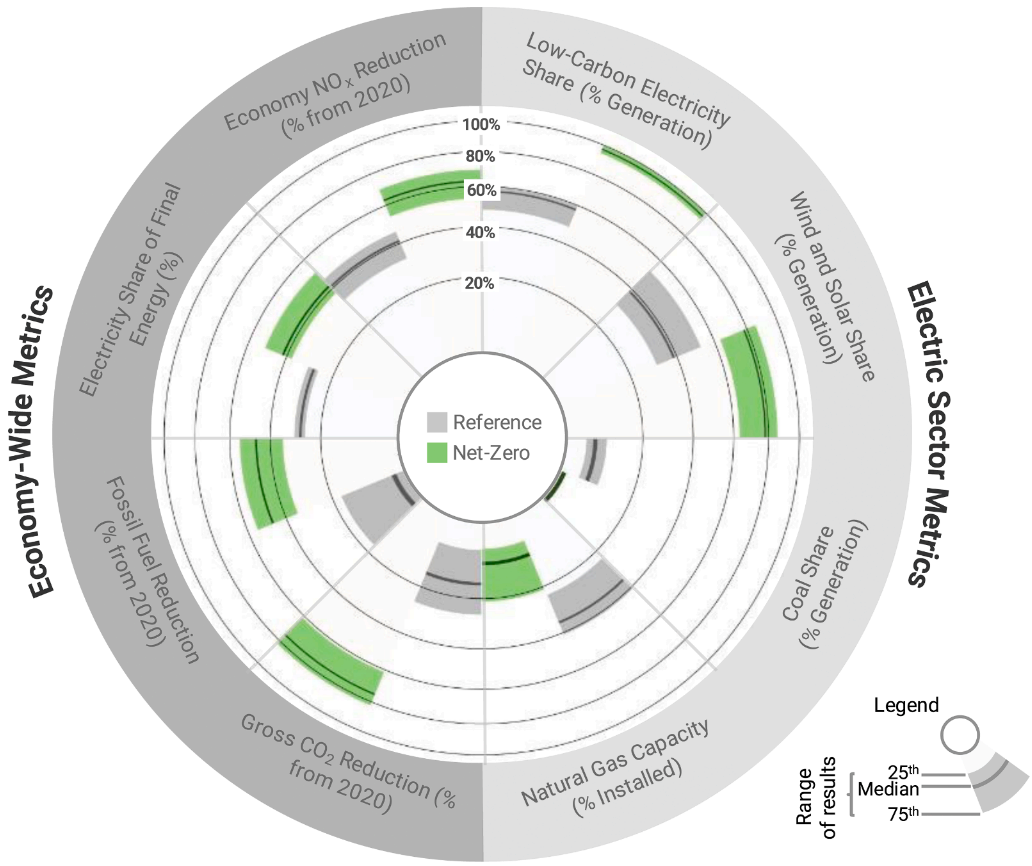

Fig. 15. Summary of key scenario metrics across models for reference (gray) and net-zero (green) scenarios in 2050. Ranges show 25th to 75th percentiles, and lines show the median across models. Metrics for the electric sector and economy are (clockwise from top) low-carbon electricity share (% generation from renewables, nuclear, and CCS), wind and solar share (% generation), coal share (% generation), natural gas capacity share (% total installed capacity), gross economy-wide CO_2 reduction (% from reported 2020 levels), fossil fuel reduction (% change in total coal, petroleum, and natural gas consumption from 2020 levels), electricity share of final energy (%), and economy-wide NO_x reduction (% from 2020 levels).

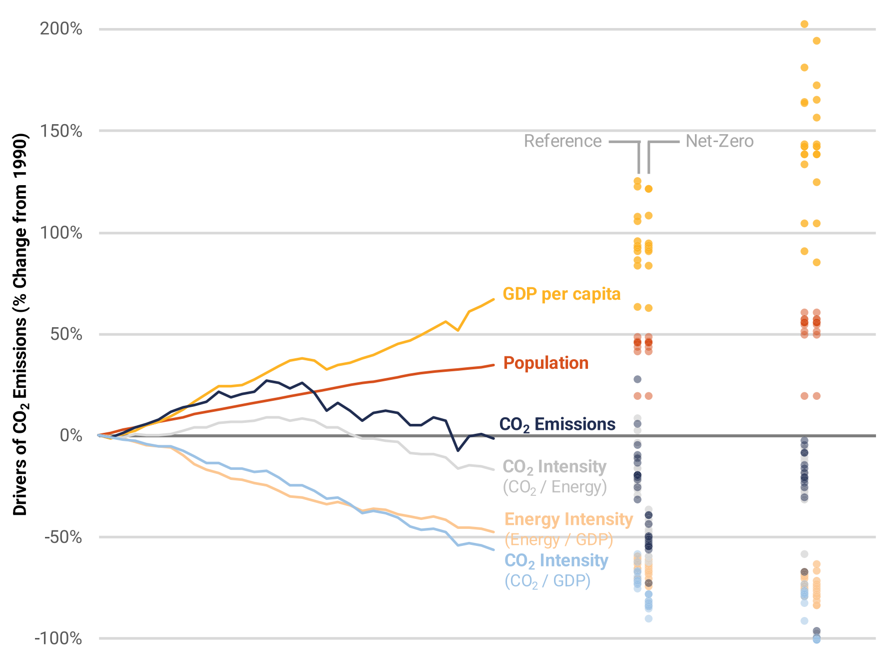

Fig. 16. Summary of drivers of CO_2 emissions changes relative to 1990 levels. Projections are shown for 2035 and 2050 across models (individual dots) in the reference and net-zero policy scenarios (first and second columns, respectively). Historical data come from Federal Reserve Economic Data (FRED) from the Federal Reserve Bank of St. Louis.

decarbonization, the fiscal impact of CDR subsidies could be reduced. Furthermore, policies that are driving down the cost of industrial sector decarbonization could help create technologies that outcompete their fossil equivalents in the market, whereas CDR subsidies will always be needed to drive CDR as there is not a large enough market for CO_2 usage for CDR to deploy on a purely market basis [21].

Historical and projected drivers of CO_2 emissions are shown in Fig. 16. This Kaya decomposition illustrates the steadily declining energy intensity of GDP and CO_2 intensity of GDP since 1990, which continue declining over time in the EMF 37 scenarios. In contrast, the CO_2 intensity of energy production and total CO_2 exhibit more variation across model projections and scenarios.

Although the EMF 37 has advanced understanding of net-zero emissions energy systems in North America, the study has highlighted additional questions and research opportunities:

- **Improving model representations of technologies and pathways to reach net-zero emissions across the economy:** The EMF 37 study has provided policy-relevant insights on net-zero systems and highlighted modeling and data gaps in representing such systems. Industrial decarbonization may see the largest benefit from model development and data gathering efforts [20], though there are areas of improvement in each sector. Having the model capability to reach very deep decarbonization in each sector is a prerequisite to understanding roles of different mitigation options and their associated economic impacts. Stress tests like the EMF 37 carbon management sensitivity without CCS [21] are good exercises to quantify system values of decarbonization resources while also assessing model capabilities in highly constrained conditions. The extent that fuel conversion pathways, technologies, and mitigation options are represented in models can impact sectoral transition insights, so future work can assess model representations for a range of mitigation options [61]. Additionally, future work should examine behavioral change and system change (e.g., lower service demand through urban design or remote work, modal shifting in mobility, structural change in industry) in greater detail [62].
- **Tracking impacts of existing and proposed policies:** Ongoing work may be needed to track the implementation gap between current policies and net-zero emissions targets, especially because proposed federal and subnational policies as well as changes in market trends can shift baselines over time [63]. In addition, as other policy objectives emerge, it will be important to understand how incentives and policies with other primary goals could alter climate policy and CO_2 reductions (e.g., technology subsidies, air quality regulations, permitting reform).
- **Modeling alternate policy pathways to reach net-zero emissions:** Although most models in this study reach net-zero emissions using a national cap-and-trade or carbon pricing policy, many proposed and enacted policies, regulations, and incentives may contribute toward reaching these goals, both at federal and subnational levels. Potential policies include carbon fees, performance standards (e.g., clean electricity standards, appliance efficiency standards, vehicle fuel economy standards, industrial emissions standards), technology subsidies for supply- and demand-side technologies (e.g., tax credits, loan guarantees, contracts for differences), innovation subsidies, permitting and interconnection reform, and procurement policies. Given political and economic challenges of stringent climate policy, analyses of alterative policy options across economic, environmental, and political criteria could be a valuable contribution.
- **Representing a greater range of carbon removal options and assessing their broader economic and environmental impacts:** These scenarios underscore the potential value of carbon removal and negative emissions options to reach net-zero emissions. However, as other studies have pointed out [64,65], these options can have economic and environmental impacts on energy-water-land systems beyond carbon emissions. This analysis focuses on technological CDR from BECCS and DAC as well as afforestation to provide negative emissions, though as the EMF 37 carbon management paper suggests [21], models vary in their coverage of CDR options. Recent work has indicated that CDR portfolios could be broader and may include biochar, enhanced weathering, and direct ocean capture with carbon storage [66], which could lower net-zero costs and feasibility issues with technological CDR. In addition, many models in this analysis assume an exogenous land sink of −800 Mt-CO_2/yr in 2050, but there is uncertainty about this value, including potential baseline assumptions and how much of this sink might contribute toward the policy goal, which provides opportunities for future work.
- **Assessing regional and local impacts:** Results in this paper focus on national-level results. However, there are considerable regional differences in mitigation costs and potential [50,24,67] as well as variation in state emissions and energy policies [68], which makes detailed regional analysis of net-zero policy impacts important for providing actionable insights.
- **Representing the fiscal system and macroeconomic interactions:** Given how these scenarios illustrate the significant fiscal impacts of net-zero policies, future work can model interactions between climate policy and the tax code [69]. This may include an assessment of macroeconomic impacts of stringent climate policies (e.g., GDP, consumption, employment) and how macroeconomic factors (e.g., interest rates) may shape energy system decarbonization. Energy systems models typically have less detail on macroeconomic interactions, while macroeconomic models often have simplified energy systems representations.
- **Evaluating net-zero CO_2 versus all greenhouse gases:** This analysis focuses on scenarios that reach net-zero CO_2 by 2050. Future work may examine economy-wide scenarios that reach net-zero emissions across all GHGs by different future years. Given the high abatement costs of some non-CO_2 GHGs, these net-zero all GHG scenarios may entail greater sectoral emissions reductions and carbon removal relative to the scenarios presented here [4].
- **Evaluating additional uncertainties and tradeoffs across other priorities:** Several uncertainties were not explicitly evaluated in these sensitivities including challenges associated with siting and permitting, availability of critical materials and skilled labor, infrastructure needs, and fuel markets. Future work can also assess impacts of other priorities, including affordability, energy security, equity and environmental justice, reliability, and resilience, especially given how there are many stakeholders for these decisions creating multiple agents with multiple objectives [70–72]. Models can provide valuable information on tradeoffs between objectives and unintended consequences, which stakeholders can combine with other relevant quantitative and qualitative information to inform their decisions.
- **Assessing how climate impacts could alter net-zero energy system decisions:** Climate change will alter the demand for energy services, particular heating and cooling and may effect the cost and performance of energy supply and demand technologies. Although the literature has compared the treatment of climate impacts across models and scenarios [73], future work can focus on how climate impacts could shape net-zero energy system decisions.
- **Understanding costs, value, and infrastructure needs for emerging technologies:** Results point to the value of emerging supply- and demand-side technologies in meeting net-zero goals—CCS, hydrogen, advanced nuclear, advanced biofuels, long-duration energy storage, DAC, and others. It is important to understand potential scalability challenges, international spillovers, material needs, supply chains, and infrastructure issues for planners and policy-makers, especially since many of the options above may require unique supply chains and supporting infrastructure for widespread deployment.

CRediT authorship contribution statement

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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.

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Data and Code Availability

The complete database from the Energy Modeling Forum 37 study is available at https://emf.stanford.edu/. Code to replicate the figures in this article can be found at the following repository: https://doi.org/10.5281/zenodo.15293816

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2025.100191.

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