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The role of electrification and the power sector in U.S. carbon neutrality

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ABSTRACT

The United States has pledged to achieve net-zero greenhouse gas emissions by 2050. We examine a series of net-zero CO_2 scenarios to investigate the impact of advanced electrification of end-use sectors on the dynamics of America's net-zero transition through 2050. Specifically, we use an integrated assessment model, GCAM-USA, to explore how advanced electrification can influence the evolution of the electricity system in pursuit of net-zero. State-level resolution for end-use demand sectors and energy transformation is a key feature of GCAM-USA that allows for elucidation of the variation in end-use electrification across states. All scenarios in this study are designed to be consistent with the modeling protocol for the Energy Modeling Forum Study 37 model inter-comparison project. Our scenarios show the scale of transformation in the power sector with average annual capacity additions reaching 121-143 GW/year and 172-190 GW/year in 2050 net-zero CO_2 scenarios and 2045 net-zero CO_2 scenarios, respectively, in the 2040s — approximately three to five times the 2021-2023 average. In 2050 net-zero CO_2 scenarios, electrification rates in 2050 range from 15-48 % for transportation, 65-83 % for buildings, and 20-38 % for industry. If net-zero CO_2 is achieved in 2045, transportation, buildings, and industry are 27-53 %, 78-84 %, and 41-53 % electrified by 2050, respectively. Advanced electrification of end-use sectors can reduce the magnitude of reliance on negative emissions by driving down residual positive emissions by mid-century. Altogether, our results demonstrate that a net-zero transition in the United States will require deep and rapid structural changes to the energy system.

1. Introduction

Goals to achieve net-zero greenhouse gas emissions (GHG) have become a central element of the global climate policy landscape, with 151 countries representing 88 % of global emissions having announced net-zero targets [12]. The United States has set a goal to achieve net-zero GHG emissions by 2050, and electrification of end-use energy demand will be a key pillar of American decarbonization efforts [31]. This raises questions about transition dynamics between sectors that can be answered through integrated assessment modeling with broad representation of all emitting sectors.

There is considerable agreement in the literature as to the importance of electrification in a net zero transition [1,2,8–10,18,26,34,35]. Specifically, a comprehensive analysis of 177 net-zero CO_2 scenarios shows that end uses are about 50 % electrified in the year of net-zero CO_2 emissions achievement [10]. The data explorer for the *Net Zero America* project reports electrified final energy shares in 2050 of 25-51 % for transportation, 71-89 % for buildings, and 21-24 % for industry in their *Less-high Electrification* and *High Electrification* scenarios [26]. Horowitz et al. [18] find that in a transition toward net-zero GHG by 2050 in the United States, over 10 % of total emissions reductions could be attributable to electrification of end-uses. While there is a clear role for electrification to play in all three end-use demand sectors — transportation, buildings, and industry — absent other changes in the energy system, this will lead to greater overall electricity demand and therefore necessitate a more rapid expansion in power sector capacity [23,28]. Improvements in efficiency of electricity use can lower the magnitude of power sector capacity growth needed to meet increased electricity demand from greater end-use electrification [11]. Across existing net-zero studies, emissions from electricity generation are reduced to either

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nearly zero or below zero by the year in which net-zero CO_2 emissions is achieved across the entire economy [5]. Improvements in renewable technologies continue to enhance opportunities for reducing emissions in the power sector. Indeed, the levelized cost of energy for new, unsubsidized utility-scale wind and solar capacity fell by 72 % and 90 %, respectively, from 2009-2021 [27], and projected future costs of these technologies continue to fall [29].

Getting to net zero in the United States will likely require the deployment of carbon dioxide removal (CDR) technologies such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) in addition to terrestrial carbon sinks [20]. However, the potential for BECCS and DACCS technologies to deploy at scale is unclear [17]. In addition, the expansion of such technologies could create trade-offs with multiple societal priorities such as biodiversity and ecosystem health [16,22]. While CDR technologies like BECCS and DACCS are unlikely to play a significant role in helping the United States achieve its 2030 economy-wide emissions target of 50-52 % below 2005 levels, these technologies may play a more significant role in America's decarbonization efforts over the longer term [13].

As part of the Energy Modeling Forum Study 37 (EMF-37) model inter-comparison project [33], we examine a series of net-zero CO_2 emissions scenarios for the United States to investigate the impact of advanced electrification of end-use sectors on the dynamics of America's net-zero transition through 2050. We also examine the potential impact of alternative technologies like advanced carbon capture and storage (CCS) and DACCS on this transition. We use the term 'advanced' to refer to modifications made to the default technological assumptions in GCAM-USA that facilitate faster uptake of electrified end-use, CCS, and DACCS technologies. The three questions guiding our analysis were: (1) What are the implications for the electricity system in the United States as it aims to achieve its net-zero goal? (2) What does advanced electrification of end-use sectors imply for the evolution of these systems? (3) How can carbon management in the form of advanced CCS technologies and DACCS affect the evolution of the electricity sector in the transition toward net zero? To answer these questions, we use an integrated assessment model (IAM) with 50-state resolution of the United States, GCAM-USA, to explore various net-zero pathways. GCAM-USA is an open-source IAM [24] covering the energy, climate, land, water, and socio-economic systems in 32 geopolitical regions of the world, plus state-level representation within the United States. State-level resolution for socioeconomic drivers, end-use demand sectors, and energy transformation is a key feature of GCAM-USA that allows for elucidation of the variation in end-use electrification across states. Net-zero emissions pathways explored in this study are first designed in terms of net-zero CO_2 emissions in 2050 rather than net-zero GHG emissions in 2050 — the official pledge of the United States — in order to be consistent with the protocol for the EMF-37 model inter-comparison exercise [6]. Additional scenarios with the United States achieving net-zero CO_2 emissions in 2045 are included to examine accelerated changes to the energy system that may occur under a 2050 net-zero GHG pathway.

This study makes several contributions over existing literature. First, this study looks more closely at electrification than previous studies employing similar models [18,31,34]. Second, with the choice of model in this study, there is greater attention paid to state-level implications, whereas previous IAM studies focus on the national scale [18,31,34]. Third, the model used here is an integrated model where various systems are hard-coupled in code and incorporate dynamic two-way feedbacks across sectors and systems in future periods (see Section 2.1 for more detail), distinguishing our analysis from other studies using more sector-specific models [26,34]. Accordingly, this model allows us to represent the demand of electricity in various end-use sectors (transportation, buildings, and industry) along with the competition of electricity with other fuels in end-use demand sectors and competition of technologies and resources to supply the demand for electricity. Finally, it is designed to be consistent with the EMF-37 protocol which enhances comparability across various other studies as part of the same protocol [6].

2. Methodology

2.1. GCAM-USA

The Global Change Analysis Model (GCAM) is an open-source IAM covering the energy, climate, land, water, and socio-economic systems, with full documentation publicly accessible online [24]. GCAM is a dynamic, recursive model with a base year of 2015 and solves in five-year time steps through 2100. GCAM has geospatial resolution of the energy and socio-economic systems across 32 geopolitical regions (including the United States), the land system across 384 subregions, tracking of water supplies through 235 hydrologic basins, and a global physical Earth system. The feature that distinguishes GCAM-USA from the core version of GCAM is that the United States geopolitical region is broken out to include spatial detail at the state-level for socio-economic assumptions, energy transformation, and end-use demand sectors. GCAM-USA also tracks all sources and sinks of CO_2 — the focus of this analysis — as well as 16 additional GHGs. Version 5.3 of GCAM-USA is used in this analysis. End-use demand sectors (transportation, buildings, and industry) in GCAM-USA represent a wide range of technologies across different subsectors that offer opportunities for electrification. Economic choice between different energy technologies in GCAM-USA that provide the same energy service are governed by logit functions described in the model documentation [24]. The logit approach avoids "winner-take-all" responses and tends to capture non-modeled considerations that impact technology competition and deployment.

Technology representation in the power sector includes coal, gas, oil, and biomass — all with and without CCS — along with nuclear, geothermal, hydro, wind, and solar. All power sector technologies are fully vintaged except for hydro which is modeled exogenously in this version of GCAM-USA. The power sector in GCAM-USA is organized into fifteen grid regions within which electricity can be freely traded [24]. Unique load duration curves constructed from hourly load data in each grid region are a model input assumed to remain constant through all model periods. The load duration curves allow for distinction between baseload, intermediate, sub-peak, and peak loads. Employing load duration curves is useful in studies using a multisector model to examine interactions across sectors and systems. However, the load duration curve approach does not capture seasonal and diurnal variation in electricity demands that electricity-centric modeling tools are especially well-suited for [3,7,21]. As Wise et al. [36] note, this approach "loses the chronology of demand and is therefore not a perfect approach for representing the time of day issues necessary for matching supplies of intermittent resources such as solar and wind to the electricity demand." Despite this limitation, the load duration curve approach allows for distinction between generation technologies with high capital costs and low fuel costs that provide baseload generation and those with comparatively lower capital costs and higher fuel costs that are more suited to provide electricity during times of peak demand. In the version of GCAM-USA used in this analysis, the power sector has grid storage as well as dedicated storage options for wind and solar technologies. Backup capacity to balance the intermittency of wind and solar is provided by gas without CCS. Recent improvements in the cost of new renewable energy capacity were included in this analysis. Additionally, the cost structure for each generation technology in the model accounts for capital costs and both fixed and variable operating and management costs. Variable renewable energy technologies also have system backup costs. In the case of switching from a non-CCS generation technology to a CCS generation technology of the same fuel type, the non-CCS technology is retired, and the new CCS technology is built to replace it. In other words, there is no retrofitting capability built into this version of the GCAM-USA.

The transportation sector represents the movement of passengers and freight. Passenger transportation includes road, rail, and air travel. Road transportation is fully vintaged and allows for competition between zero-emission vehicles (ZEVs), such as battery electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs), and internal combustion engine vehicles (ICEVs) within markets for light-duty vehicles (LDVs) and buses. This allows for policies targeting specified ZEV sales shares to be represented in GCAM-USA. More specifically, the LDV market includes BEVs, FCEVs, and ICEVs, while the bus market allows for competition between BEVs, ICEVs, and buses fueled by natural gas. Non-vintaged two- and three-wheeled transportation options are also available in GCAM-USA with competition between BEVs and ICEVs. Other non-vintaged passenger transportation options in GCAM-USA include walking, cycling, passenger rail from electricity and liquid fuels, and domestic and international aviation powered by liquid fuels. Freight transportation via road includes light-, medium-, and heavy-duty trucks that are fully vintaged with competition between BEVs and ICEVs. The remaining freight transportation technologies in GCAM-USA are domestic shipping, international shipping, and rail — all non-vintaged and running on liquid fuels.

The model also contains detailed technological representation of a wide range of energy services in the residential and commercial buildings sectors including space heating and cooling, water heating, cooking, lighting, refrigeration, and appliances. Space heating in buildings is represented by electric heat pumps and furnaces fueled by gas, fuel, wood, electricity, or coal, along with high-efficiency options for fuel (residential only) and gas furnaces. Space cooling technologies include regular and high-efficiency air conditioning, plus gas cooling options in commercial buildings only. Water heating technologies include electric heat pumps and gas, fuel, and electric resistance water heaters. High-efficiency gas water heaters are available for all buildings, and residential buildings also have high-efficiency fuel and electric resistance water heaters. Cooking service is provided by electric, gas, or liquified petroleum gas (residential only) ovens, with high-efficiency options available for gas, liquified petroleum gas (residential only), and electric (commercial only). Three technologies are included for building lighting in GCAM-USA: fluorescent, incandescent, and solid state. Regular and high-efficiency refrigeration options are available for all buildings. Residential buildings also include a range of additional appliances powered by electricity: clothes dryers, clothes washers, computers, dishwashers, freezers, furnace fans, and televisions, with high-efficiency options for clothes dryers, clothes washers, dishwashers, and freezers. Commercial buildings also include office equipment and regular and high-efficiency ventilation powered by electricity. Building sector technologies in GCAM-USA are fully vintaged except for computers, furnace fans, office equipment, and televisions. All additional energy service in each of residential and commercial buildings is aggregated into a non-vintaged "other" category with inputs from electricity, gas, and liquid fuels.

The industry sector has explicit representation of cement and fertilizer production while the rest of the industry sector is aggregated into a single subsector with energy inputs from biomass, coal, electricity, gas, hydrogen, and liquid fuels. Energy for cement production is provided by a mix of biomass, coal, electricity, gas, or liquid fuels, while gas is the sole energy input for fertilizer production. Adjustments to technological representation were made to include direct air capture as an additional mitigation option in this analysis.

Dynamic two-way feedbacks between sectors and systems are an important element of GCAM-USA. For instance, changes in electricity demands driven by varying rates of end-use sector electrification in a future model period will endogenously result in changes in supply. At the same time, changes in electricity prices will affect the role of electricity in end-use sectors. Another example is bioenergy. In any given model time step, bioenergy is consumed in the energy sector but is produced in the land module of GCAM which represents competition for land across all uses of land including agriculture and afforestation.

2.2. Scenario design

Our analysis consists of ten scenarios, as shown in Table 1. In the *NT-RefElecAll* scenario, we do not model an emissions target for the United States. In the *NZ50-RefElecAll, NZ50-AdvElecBld, NZ50-AdvElecInd, NZ50-AdvElecTrn, NZ50-AdvElecAll*, and *NZ50-AdvElecAll-AdvCM* scenarios, we model a 2050 net-zero CO_2 target for the United States. We again note that the choice to model a net-zero CO_2 target is to be consistent with the EMF-37 protocol as it is a model inter-comparison project and that this net-zero CO_2 target differs from the official United States net-zero GHG target. To explore a more ambitious net-zero CO_2 timeline that would be implicit in achievement of net-zero GHG emissions by 2050, three scenarios are modeled with the United States achieving net-zero CO_2 emissions in 2045: *NZ45-RefElecAll, NZ45-AdvElecAll*, and *NZ45-AdvElecAll-AdvCM*. The 2050 net-zero CO_2 emissions constraint is implemented as a linear reduction from historical emissions in 2020 to the achievement of the current NDC in 2030 (50-52 % below 2005 levels), and then a continued linear reduction from there to net-zero CO_2 emissions in 2050. Under the 2045 net-zero CO_2 emissions constraint, CO_2 emissions are reduced linearly from the 2030 NDC level to net-zero CO_2 in 2045 and continue linearly downward to -989 $MtCO_2$ in 2050.

For the electrification of end-use demand sectors, the reference electrification assumptions in the *NT-RefElecAll, NZ50-RefElecAll*, and *NZ45-RefElecAll* scenarios are the default assumptions in GCAM-USA. These default electrification assumptions in transportation, buildings, and industry are modified to create our advanced electrification assumptions for the *NZ50-AdvElecAll, NZ50-AdvElecAll-AdvCM, NZ45-AdvElecAll*, and *NZ45-AdvElecAll-AdvCM* scenarios (see SI Tables S1-S4

Table 1
Scenario matrix. NT = no target. NZ = net-zero. Bld = buildings. Ind = industry. Trn = transportation. CCS = carbon capture and storage. DACCS = direct air carbon capture and storage. $MtCO_2$ = million metric tons of carbon dioxide. 'Reference' refers to default technological assumptions in GCAM-USA. 'Advanced' refers to modifications made to the default technological assumptions in GCAM-USA to facilitate faster uptake of electrified end-use or carbon management technologies.

Scenario Name	USA Emissions Target	End-Use Electrification	CCS	DACCS Availability
NT-RefElecAll	None	Reference: Bld, Ind, Trn Advanced: none	None	No
NZ50-RefElecAll	2050 Net-zero CO_2	Reference: Bld, Ind, Trn Advanced: none	Reference	Yes, 200 $MtCO_2$
NZ50-AdvElecBld	2050 Net-zero CO_2	Reference: Ind, Trn Advanced: Bld	Reference	Yes, 200 $MtCO_2$
NZ50-AdvElecInd	2050 Net-zero CO_2	Reference: Bld, Trn Advanced: Ind	Reference	Yes, 200 $MtCO_2$
NZ50-AdvElecTrn	2050 Net-zero CO_2	Reference: Bld, Ind Advanced: Trn	Reference	Yes, 200 $MtCO_2$
NZ50-AdvElecAll	2050 Net-zero CO_2	Reference: none Advanced: Bld, Ind, Trn	Reference	Yes, 200 $MtCO_2$
NZ50-AdvElecAll-AdvCM	2050 Net-zero CO_2	Reference: none Advanced: Bld, Ind, Trn	Advanced	Yes, 400 $MtCO_2$
NZ45-RefElecAll	2045 Net-zero CO_2	Reference: Bld, Ind, Trn Advanced: none	Reference	Yes, 200 $MtCO_2$
NZ45-AdvElecAll	2045 Net-zero CO_2	Reference: none Advanced: Bld, Ind, Trn	Reference	Yes, 200 $MtCO_2$
NZ45-AdvElecAll-AdvCM	2045 Net-zero CO_2	Reference: none Advanced: Bld, Ind, Trn	Advanced	Yes, 400 $MtCO_2$

for technology cost assumptions in GCAM-USA). In the transportation sector, we model our advanced electrification case through accelerated cost reductions and increased consumer preferences for ZEVs. Sales shares for passenger ZEVs are assumed to reach 50 % of the LDV market in 2030 and 95 % in 2035 to be consistent with the United States Long-Term Strategy (LTS) [18,31]. ZEV sales shares of freight trucks are modeled to reach 50 % by 2035 and 100 % by 2045 in the advanced electrification case. In buildings, advanced electrification is modeled by reducing sales shares for fossil fuel technologies in space heating and water heating to reach zero by 2050, thus driving the sales share for electric technologies to nearly 100 % by mid-century. And we model advanced electrification in the industry sector by increasing preferences for electric technologies relative to non-electric technologies. The impact of advanced electrification of individual end-use sectors is explored in the *NZ50-AdvElecBld, NZ50-AdvElecInd*, and *NZ50-AdvElecTrn* scenarios.

Assumptions for carbon management pertain to both CCS and DACCS. For the *NT-RefElecAll* scenario, where there is no emissions target, buildout of CCS or DACCS is not triggered in the model. In all scenarios, except for *NZ50-AdvElecAll-AdvCM* and *NZ45-AdvElecAll-AdvCM*, our reference carbon management assumptions include default parameters for CCS in GCAM-USA and achievable annual CO_2 removals from DACCS are assumed not to exceed 200 Mt in 2050. The advanced carbon management assumptions in the *NZ50-AdvElecAll-AdvCM* and *NZ45-AdvElecAll-AdvCM* scenarios include reduced CCS costs and a doubling of the ceiling for CO_2 removals from DACCS to 400 $MtCO_2$ annually by 2050. The upper limit in 2050 of 400 $MtCO_2$/year on removals from DACCS is consistent with previous studies [16,18,31]. All DACCS energy inputs are modeled based on previously published literature [15,16]. Our central scenarios assume limited expansion of BECCS. We include additional simulations in the SI that allow for the higher deployment of BECCS by relaxing this constraint such that bioenergy can expand up to one billion tons of dry biomass (SI Figures S1-S3) per analysis by the United States Department of Energy [25]. The total amount of CDR in 2050 from terrestrial carbon sinks, BECCS, and DACCS in our three net-zero scenarios falls within the range explored in the United States LTS [18,31].

The impacts of the COVID-19 pandemic on end-use energy demand in 2020 and associated recovery trajectories are included in all modeled scenarios [37]. We also assume a complete phase-out of coal-fired electricity generation without CCS by 2030 in the United States in all net-zero CO_2 scenarios. Furthermore, while we acknowledge the importance of the Inflation Reduction Act (IRA) as a driver of emissions reductions in the near term [4], we do not explicitly model its climate and energy provisions in this analysis as the focus here is on the longer-term dynamics of America's net-zero transition. The omission of the IRA's climate and energy provisions is motivated by the need for consistency with other studies that are part of the EMF-37 model inter-comparison project. For the same reason, state-level policies and emissions targets are not explicitly represented.

3. Results and discussion

3.1. CO_2 emissions by sector

In the *NZ50-RefElecAll* scenario, residual positive emissions in 2050 equal 1,766 $MtCO_2$ and are balanced by an equal amount of negative emissions from a combination of land-use, land-use change, and forestry (LULUCF), BECCS, and DACCS (Fig. 1). Advanced electrification of end-use sectors leads residual positive emissions in 2050 to be 10 % lower in the *NZ50-AdvElecAll* scenario than in the *NZ50-RefElecAll* scenario, thus reducing the pressure to scale up negative emissions from BECCS and LULUCF. In the *NZ50-AdvElecAll-AdvCM* scenario, the magnitude of the contribution to negative emissions from LULUCF is 120 $MtCO_2$ smaller than in the *NZ50-AdvElecAll* scenario. Furthermore, the total amount of CDR from BECCS and DACCS over the 2021-2050 period is 6,778 $MtCO_2$ in the *NZ50-RefElecAll* scenario, but it is only 5,334 $MtCO_2$ in the *NZ50-AdvElecAll* scenario. Thus, a 21 % reduction in the amount of required CDR from BECCS and DACCS is attributable to advanced electrification of end-use sectors. In transportation and buildings, CO_2 emissions are 48 % and 36 % lower, respectively, in the *NZ50-AdvElecAll* scenario than in the *NZ50-RefElecAll* scenario. For scenarios in which only one sector has advanced electrification assumptions (*NZ50-AdvElecBld, NZ50-AdvElecInd*, and *NZ50-AdvElecTrn*) emissions in the other sectors with reference assumptions for end-use electrification are higher than their respective emissions in the *NZ50-RefElecAll* scenario. This dynamic is most pronounced in the *NZ50-AdvElecTrn* scenario because the absolute reduction in transportation emissions resulting from advanced electrification assumptions is larger than the sectoral emissions impact of advanced electrification in only buildings or industry. Net-zero 2045 scenarios are assumed to reach -989 $MtCO_2$ in 2050. In 2050, residual positive emissions in the *NZ45-RefElecAll* scenario are 685 $MtCO_2$ lower than they are in the *NZ50-RefElecAll* scenario. This implies that nearly 70 % of the additional effort to reach the lower 2050 net CO_2 emissions level is achieved through CO_2 emissions reductions, while the remaining 30 % is achieved through increased CO_2 removals. Compared to the *NZ50-AdvElecAll* scenario in 2050, residual positive emissions are 535 $MtCO_2$ lower in the *NZ45-AdvElecAll* scenario, which amounts to 54 % of the 989 $MtCO_2$ reduction in 2050 net CO_2 emissions between the two scenarios.

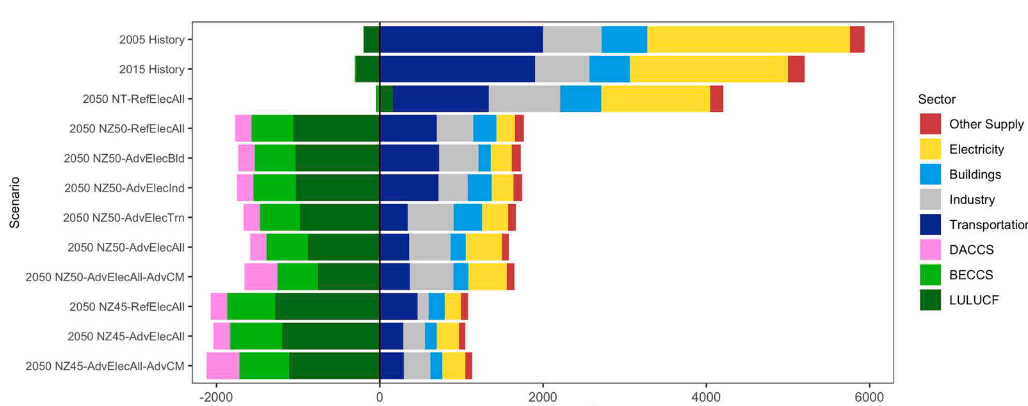

Fig. 1. CO_2 emissions by sector. The net-zero in 2050 (*NZ50*) scenarios show balanced residual positive emissions and negative emissions in 2050. The net-zero in 2045 (*NZ45*) scenarios show balanced residual positive emissions and negative emissions in 2045 and net-negative emissions in 2050. Historical emissions and the *NT-RefElecAll* scenario show net-positive emissions. DACCS = direct air carbon capture and storage. BECCS = bioenergy with carbon capture and storage. LULUCF = land use, land-use change, and forestry. A full time series for this figure is shown in SI Figure S4.

3.2. Costs associated with net-zero pathways

The carbon prices associated with net-zero CO_2 emissions are indicative of the challenges and costs associated with the transition to net zero. GCAM-USA calculates the minimum level of the carbon price needed in each model period such that emissions to not exceed the level of the emissions constraint. The resulting output carbon price represents a quantitative point of comparison between scenarios for the relative strength of climate policy needed to deliver a given emissions reduction. However, the level of the GCAM-USA output carbon price should not be interpreted as the level of carbon tax needed in the real world to achieve a given emissions target. Compared to the *NZ50-RefElecAll* scenario, advanced electrification of end-use sectors leads to a 46 % reduction in the mid-century carbon price in the *NZ50-AdvElecAll* scenario (Fig. 2). The significantly lower carbon price in the *NZ50-AdvElecAll* scenario is attributable to lower end-use electrification costs in transportation (see SI Table S1) and significantly higher flexibility for fuel switching away from fossil fuels in buildings, transportation, and industrial sectors. As described in Section 2.2, preferences among different technology choices are modified such that barriers to electrification are reduced in advanced electrification scenarios, thereby resulting in lower needed carbon prices for the emissions constraints to be achieved in those scenarios. As advanced CCS and increased DACCS availability provide additional flexibility for achieving net-zero CO_2 emissions, the carbon price is even lower in the *NZ50-AdvElecAll-AdvCM* scenario. Carbon prices in 2050 for the *NZ45-RefElecAll, NZ45-AdvElecAll*, and *NZ45-AdvElecAll-AdvCM* scenarios are more than twice as high as in their corresponding net-zero 2050 scenarios (*NZ50-RefElecAll, NZ50-AdvElecAll*, and *NZ50-AdvElecAll-AdvCM*). Among scenarios with consistent net-zero assumptions, inclusion of additional advanced end-use electrification or carbon management assumptions expands the range of options for achieving emissions reductions, thus lowering the additional carbon prices needed for the net-zero targets to be achieved. Note that the carbon prices in our study are not designed to model specific policy instruments but are rather reflective of the scale the challenges associated with the transitions. The *NT-RefElecAll* scenario does not have an associated carbon price because there is no emissions reduction target.

3.3. Electricity generation

Total electricity demand in the United States did not vary considerably from 2005-2015 as electrification of end-use sectors did not increase appreciably (top panel of Fig. 3). However, during that period, the relative share of gas in the electricity generation fuel mix increased as falling gas costs supplanted electricity generation from coal (bottom panel of Fig. 3). The *NZ50-RefElecAll* scenario requires a 25 % increase in total electricity demand in 2050 compared to the *NT-RefElecAll* scenario (Fig. 3), and the *NZ50-AdvElecAll* scenario requires nearly a 50 % increase from the *NT-RefElecAll* scenario. On a more ambitious net-zero timeline, midcentury electricity demand in the *NZ45-RefElecAll* scenario is 29 % higher than in the *NZ50-RefElecAll* scenario, and 17 % higher in the *NZ45-AdvElecAll* scenario than in the *NZ50-AdvElecAll* scenario. To match the growth in electricity demand across all net-zero scenarios, especially in the advanced electrification scenarios, a massive buildout of wind and solar capacity would be needed, along with expanded capacity from natural gas with CCS. In 2050, scenarios with advanced electrification of end-use sectors show higher levels of emissions in the electricity sector (Fig. 1) due to some of the consequent increase in electricity demand being met, in part, through continued levels of electricity generation from gas capacity without CCS (Fig. 3). A decline in nuclear power generation is seen in all scenarios except *NZ45-RefElecAll*. While it is true that greater capacity for CCS and DACCS can provide additional flexibility in achieving net zero, the absolute amount of electricity generation from wind and solar in the *NZ50-AdvElecAll-AdvCM* scenario in 2050 is only 5 % lower than in the *NZ50-AdvElecAll* scenario. Growth of electricity generation from gas without CCS through 2050 in the *NT-RefElecAll* scenario would likely be lower if the IRA were represented in our analysis [4].

A net-zero transition in the United States will require significant capacity additions in the power sector. Average annual capacity additions from 2021-2030 range from 61-74 GW/year across all net-zero scenarios, with the variation driven by the impact of electrification rates (Fig. 4). The needed near-term rate of capacity addition in these scenarios is nearly double the 38 GW/year average annual rate of capacity addition from 2021-2023 [32]. This underscores the pressure on building out power sector capacity during this decade. But over the longer term, annual capacity additions over 2041-2050 average 121-143 GW/year in 2050 net-zero CO_2 scenarios and 172-190 GW/year in 2045 net-zero CO_2 scenarios. Wind and solar accounted for just over half of capacity additions from 2005-2023, but account for nearly 80 % of capacity additions from 2021-2050 in the *NZ50-RefElecAll* scenario. In the *NZ50-AdvElecAll* scenario, average annual capacity additions are almost 10 GW/year higher than in the *NZ50-RefElecAll* scenario, highlighting the impact of advanced electrification on the growth rate of power sector capacity. Greater installation of wind and solar capacity accounts for over half of the difference in power sector capacity additions in the *NZ50-AdvElecAll* scenario, along with addition of non-CCS gas capacity that is similar to the historical average. Additionally, there is a steady increase in the rate of average annual capacity addition from technologies with CCS from the *NZ50-RefElecAll* scenario to the *NZ50-AdvElecAll* scenario to the *NZ50-AdvElecAll-AdvCM* scenario. While the positive values in Fig. 4 represent average annual capacity additions, the negative values signify average annual prematurely retired power sector capacity. Fully vintaged power sector capacity allows for calculation of expected shutdown timelines for capacity installed in each model period.

Prematurely retired capacity is equivalent to the amount of power sector capacity that shuts down before the end of its expected lifetime in the model if variable costs from fuels and carbon prices on emissions approach or eclipse the revenue generated by the electricity generation from that installed capacity. The scale of prematurely retired coal capacity without CCS is significant through 2030 due to the modeled

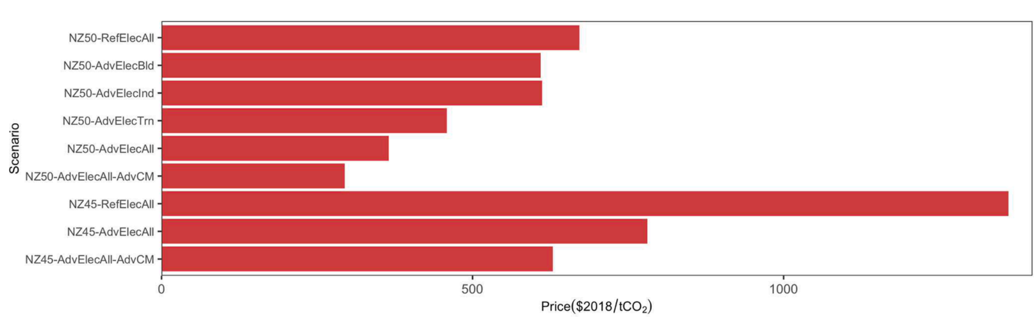

Fig. 2. Carbon prices in 2050. Advanced end-use electrification and carbon management assumptions are associated with lower carbon prices in our scenarios. A full time series for this figure is shown in SI Figure S5.

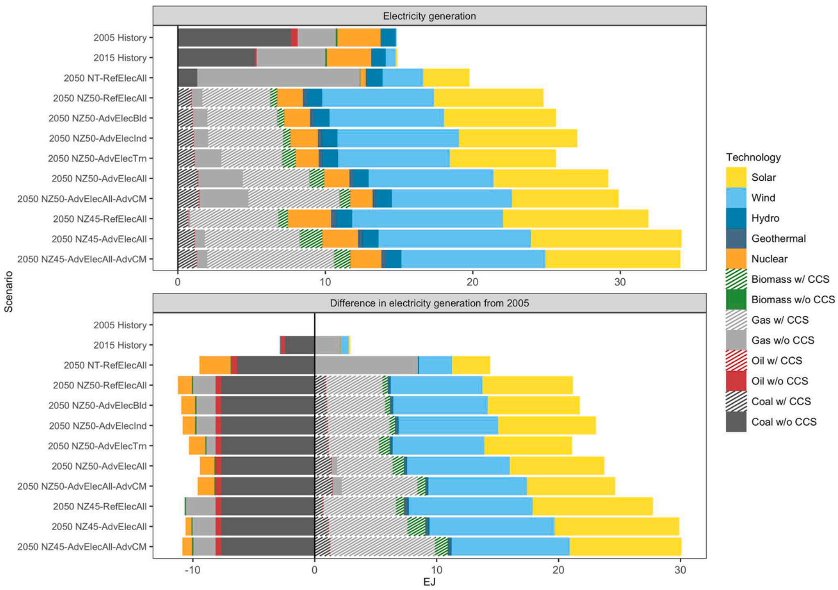

Fig. 3. Electricity generation by technology (top panel) and difference in electricity generation from 2005 by technology (bottom panel). Total electricity demand in 2050 in the *NZ50-RefElecAll* and *NZ50-AdvElecAll* scenarios is 25 % higher and 50 % higher, respectively, than it is in 2050 in the *NT-RefElecAll* scenario. w/o CCS = without carbon capture and storage. w/ CCS = with carbon capture and storage. A full time series for this figure is shown in SI Figure S6.

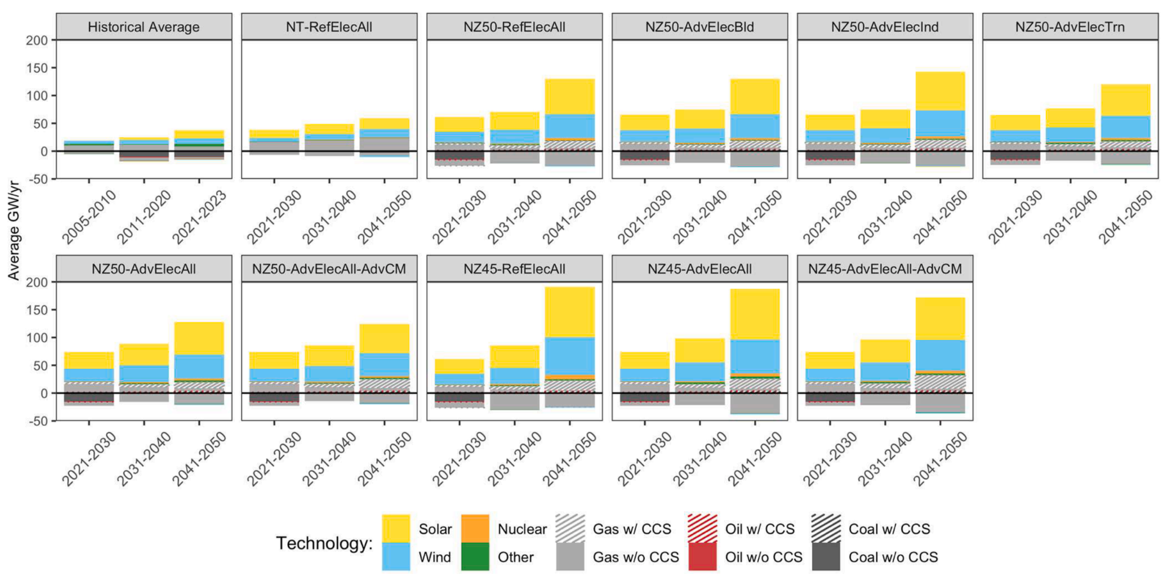

Fig. 4. Average annual capacity additions (positive values) and premature retirements (negative values) in the power sector compared with historical averages [32]. Average annual capacity additions reaching 121-143 GW/year and 172-190 GW/year in 2050 net-zero CO_2 and 2045 net-zero CO_2 scenarios, respectively, in the 2040s — approximately three to five times the average annual rate of capacity addition from 2021-2023. w/o CCS = without carbon capture and storage. w/ CCS = with carbon capture and storage. A full time series for total power sector capacity is shown in SI Figure S7.

phaseout. In most net-zero scenarios, the scale of prematurely retired capacity from gas without CCS grows each decade, accompanied by growth in gas with CCS capacity. As noted in the Section 2.1, this version of GCAM-USA does not have the capability to retrofit a non-CCS gas plant with CCS, thus the scale of premature retired gas without CCS capacity would likely be smaller in the real-world due to CCS retrofits for plants where this is a feasible option. The amount of prematurely retired gas without CCS capacity is comparatively smaller in the *NZ50-AdvElecAll* scenario than in the *NZ50-RefElecAll* scenario, because a greater amount of existing capacity is retained to meet higher electricity demand. This increased retention of gas & oil without CCS capacity leads to higher power sector emissions in the *NZ50-AdvElecAll* scenario compared to the *NZ50-RefElecAll* scenario that are partly compensated by lower emissions from transportation and buildings due to advanced electrification (Fig. 1).

3.4. Electricity prices

National weighted-average retail electricity prices to buildings are higher in all net-zero scenarios than in the *NT-RefElecAll* scenario (Fig. 5) because capacity additions are in alternative and more expensive technologies (Fig. 4) and carbon prices are driving up marginal costs. Compared to the *NZ50-RefElecAll* scenario, electricity prices in 2050 are nearly 8 % lower in the *NZ50-AdvElecAll* scenario and even lower in the *NZ50-AdvElecAll-AdvCM* scenario. Such a price reduction can be explained by the fact that the *NZ50-AdvElecAll* and *NZ50-AdvElecAll-*

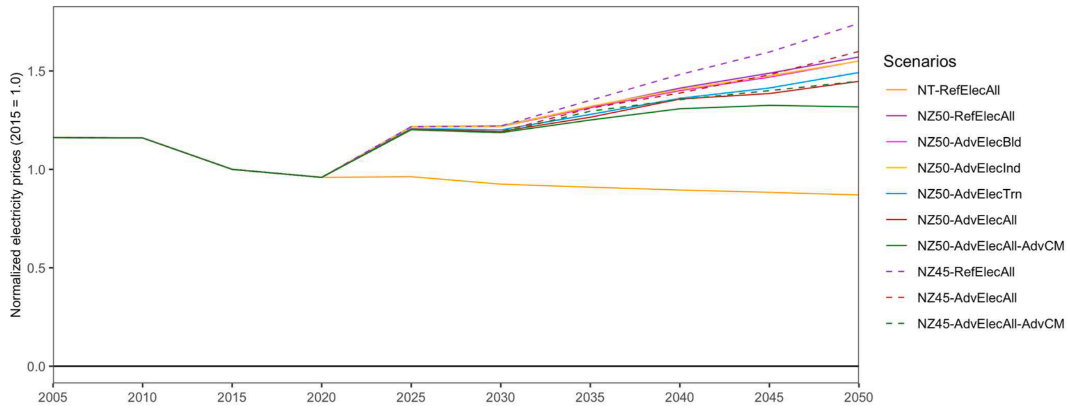

Fig. 5. National average retail electricity price weighted by state electricity consumption, normalized to the 2015 value (2015 = 1.0). Net-zero (*NZ*) scenarios have higher electricity prices than the *NT-RefElecAll* scenario. Electricity prices are lower in the *NZ50-AdvElecAll* scenario than in the *NZ50-RefElecAll* scenario, and lower yet in the *NZ50-AdvElecAll-AdvCM* scenario.

AdvCM scenarios have lower carbon prices than the *NZ50-RefElecAll* scenario (Fig. 2). Since both scenarios see investment in CCS technologies, especially gas with CCS, and their costs along with the carbon prices are accounted for in the electricity prices, the resulting electricity prices are successively lower in the *NZ50-AdvElecAll* and *NZ50-AdvElecAll-AdvCM* scenarios. Achieving net-zero CO_2 in 2045 results in mid-century electricity prices being 10 % higher than in comparative 2050 net-zero CO_2 scenarios.

3.5. End-use electrification

Transportation final energy is 15-16 % electrified in 2050 for scenarios with the United States achieving net-zero CO_2 in 2050 with reference electrification assumptions and 45-48 % with advanced electrification assumptions (leftmost panel of Fig. 6). At the state level, the share of final energy from electricity in the median state's transportation sector in 2050 is 18 % in the *NZ50-RefElecAll* scenario and 62 % in the *NZ50-AdvElecAll* scenario (SI Figure S8). In the LDV market, ZEVs account for 39 % of LDV sales in 2030 in the *NZ50-RefElecAll* scenario and climb to 85 % of LDV sales by 2050. LDV electrification proceeds faster in the *NZ50-AdvElecAll* scenario, with ZEVs reaching 53 % of new LDV sales in 2030, 96 % in 2035, and 100 % in 2040 (SI Figure S9). Across the entire stock, 97 % of LDVs on the road in 2050 are ZEVs in the *NZ50-AdvElecAll* scenario, compared to 72 % in the *NZ50-RefElecAll* scenario (SI Figure S10). For freight transportation via trucks, there is a stark difference in ZEV market penetration between the *NZ50-RefElecAll* and *NZ50-AdvElecAll* scenarios. New sales for ZEV trucks reach 51 % of the road freight market in 2035 and 100 % in 2045 in the *NZ50-AdvElecAll* scenario, but struggle to reach just 10 % by 2050 in the *NZ50-RefElecAll* scenario (SI Figure S11). As a result, freight road service from the total stock of trucks on the road is almost fully electrified by 2050 in the *NZ50-AdvElecAll* scenario, while the *NZ50-RefElecAll* scenario is characterized by minimal electrification of trucks (SI Figure S12).

The buildings sector, unlike transportation, already has a fair degree of electrification, with 53 % of buildings final energy across the United States electrified in 2015 (middle panel of Fig. 6). By 2050, the electrification rate in the buildings sectors rises to 65-71 % for 2050 net-zero CO_2 scenarios with reference electrification assumptions and 80-83 % with advanced electrification in buildings. Of the residential and commercial buildings services represented in GCAM-USA, electrification provides the greatest opportunity for emissions reduction in heating services. In 2050, the median state's share of buildings final energy from electricity reaches 72 % and 81 % in the *NZ50-RefElecAll* and *NZ50-AdvElecAll* scenarios, respectively (SI Figure S13). With low demand for heating services, Florida has the highest rate of buildings electrification in the United States in 2050 in both the *NZ50-RefElecAll* and *NZ50-AdvElecAll* scenarios, with 92 % of final energy in buildings coming from electricity. And despite having the lowest share of buildings final energy from electricity in 2050 in the *NZ50-RefElecAll* scenario, Alaska shows the largest improvement in buildings sector electrification from 2015, doubling from 23 % to 46 %.

The median state-level share of final energy from electricity in the industry sector rises to 41 % in the *NZ50-RefElecAll* scenario in 2050 but falls to 35 % in the *NZ50-AdvElecAll* scenario (SI Figure S14). Industry electrification by state in 2015 ranges from 1 % in Alaska to 46 % in Nevada. There is considerable variability across states for total final energy demand for industrial activities. In the *NZ50-RefElecAll* and *NZ50-AdvElecAll* scenarios, six states — Texas, Louisiana, California, Pennsylvania, Ohio, and Indiana — collectively account for half of national industrial energy demand. Nationwide electrification in industry nearly doubles from 16 % in 2015 to 30 % and 29 % in 2050 in the *NZ50-RefElecAll* and *NZ50-AdvElecAll* scenarios, respectively (rightmost panel

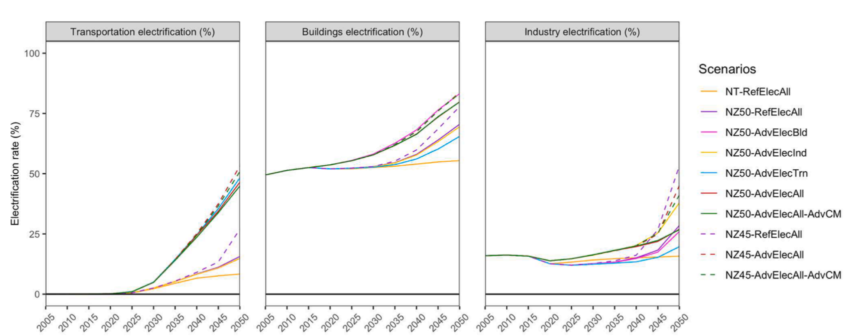

Fig. 6. Electrification rates across end-use sectors. Additional figures showing electrification rates across end-use sectors for all ten scenarios in all states are shown in SI Figures S8 and S13-14, and figures showing final energy by fuel for each end-use sector are shown in SI Figures S15-17.

of Fig. 6). While the overall amount of electrified energy service in industry is higher in the *NZ50-AdvElecAll* scenario than in the *NZ50-RefElecAll* scenario, the *NZ50-AdvElecAll* scenario's share of industrial final energy from electricity is lower than in the *NZ50-RefElecAll* scenario. While this may appear counterintuitive, it is because a higher carbon price drives a larger demand reduction in industrial energy service from emitting sources is needed in the *NZ50-RefElecAll* scenario for net-zero CO_2 to be achieved. But in the *NZ50-AdvElecAll* scenario, deeper emissions reductions in transportation and buildings reduce pressure on emissions reductions in industry and thus the industry demand reduction seen in the *NZ50-RefElecAll* scenario is not observed in the *NZ50-AdvElecAll* scenario. An important caveat of this analysis is that the industrial sector in the version of GCAM-USA used in this study includes explicit representation of only the cement and fertilizer industries. The rest of the industrial sector is modeled in an aggregate fashion without explicit representation of services and technological substitution.

In 2045 net-zero CO_2 scenarios, the midcentury electrification rates are higher for all end-use sectors compared to their respective 2050 net-zero CO_2 scenarios with consistent electrification and carbon management assumptions. The increase in end-use 2050 electrification rates between comparable 2050 and 2045 net-zero scenarios is most pronounced between the *NZ50-RefElecAll* and *NZ45-RefElecAll* scenarios. Advanced electrification of only one end-use sector typically leads to reduced pressure on electrification in the other two end-use sectors. This is particularly the case with the buildings electrification rates being falling from 71 % in the *NZ50-RefElecAll* scenario to 65 % in the *NZ50-AdvElecTrn* scenario in 2050. Similarly, the 2050 industry electrification rate falls from 29 % to 20 % across the same two scenarios.

The market penetration of ZEVs does not vary considerably from one state to another because there were very few ZEVs on the road in 2015 and little variation in the LDV market across states. As a result, by midcentury in the *NZ50-AdvElecAll* scenario when the LDV market is nearly 100 % electrified, the states with lower transportation sector electrification are those with a large share of transportation service from other modes that are more difficult to decarbonize such as aviation and shipping (leftmost column of Fig. 7). Accordingly, as the LDV market becomes more electrified, the variation in state-level final energy from electricity in the transportation sector begins to increase. There is considerable state-level variation in buildings sector electrification (middle column of Fig. 7). In 2015, states in the southeast had higher rates of buildings electrification because of their low demand for heating services, while other states that have extensive networks of natural gas distribution pipelines are less electrified. The states with the lowest electrification rates in 2015 are Alaska and those in the northeast where heating oil is more common. Considerable regional variation exists in industry electrification rates in 2015 and at net-zero in 2050 with both reference and advanced electrification (rightmost column of Fig. 7).

3.6. *Fossil fuel consumption*

An additional implication of advanced electrification of end-use sectors is that oil consumption is significantly lower (24 % in 2050) in the *NZ50-AdvElecAll* scenario than in the *NZ50-RefElecAll* scenario, which indicates that it may reduce the vulnerability of the United States to future energy security risks (leftmost panel of Fig. 8). Transport electrification is the primary driver of the reduction in oil consumption through 2050, and this is more pronounced in the *NZ50-AdvElecAll* scenario than in the *NZ50-RefElecAll* scenario (SI Figure S15). Gas consumption remains at a level similar to today across our 2050 net-zero CO_2 scenarios, representing a considerable departure from the continued growth of gas consumption in the *NT-RefElecAll* scenario (middle panel of Fig. 8). Increasing gas consumption in the electricity sector, and to a lesser extent, in industry, is offset by significantly reduced gas consumption in the building sector due to electrification. As noted in the discussion of Fig. 3, the growth of electricity generation from gas without CCS would likely be smaller in the *NT-RefElecAll* scenario if it included the climate and energy provisions of the IRA [4]. However, among 2050 net-zero CO_2 scenarios, gas consumption is slightly higher with advanced electrification, which is attributable to the increased reliance on gas in electricity generation to meet the greater electricity demand from increased electrification of end-use sectors. Gas consumption is even higher in the *NZ50-AdvElecAll-AdvCM* scenario due to a greater use of gas with CCS in the power sector. Gas consumption begins to decline more steeply post-2030 in 2045 net-zero CO_2 scenarios without advanced carbon management assumptions (i.e., in the

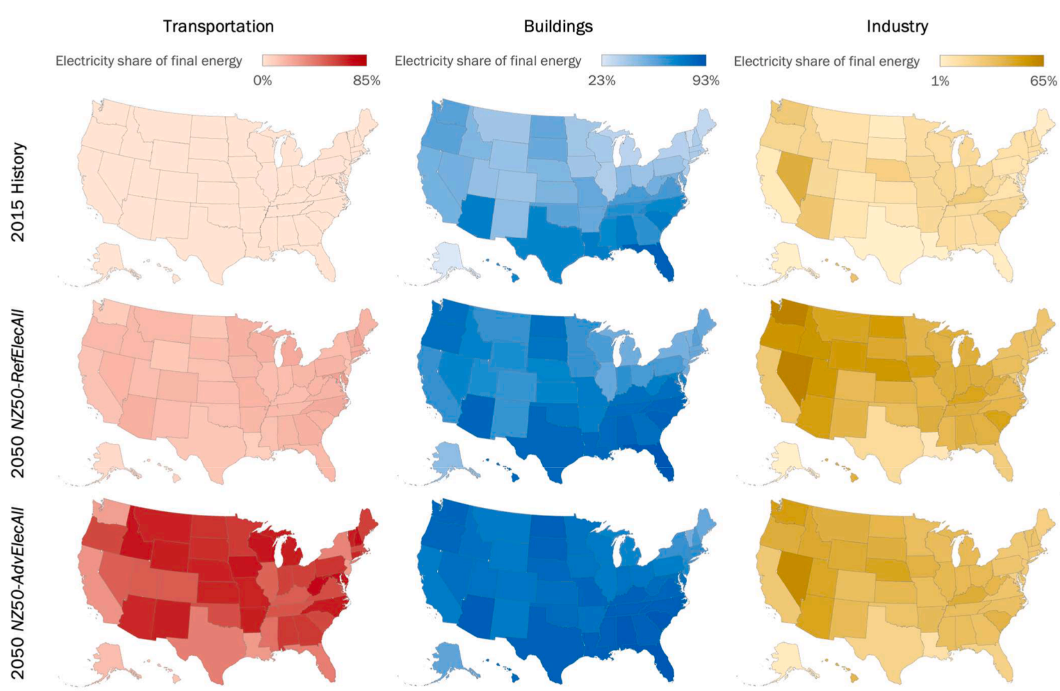

Fig. 7. State-level share of final energy from electricity in end-use sectors. Transportation is shown in the leftmost column, buildings in the middle column, and industry in the rightmost column.

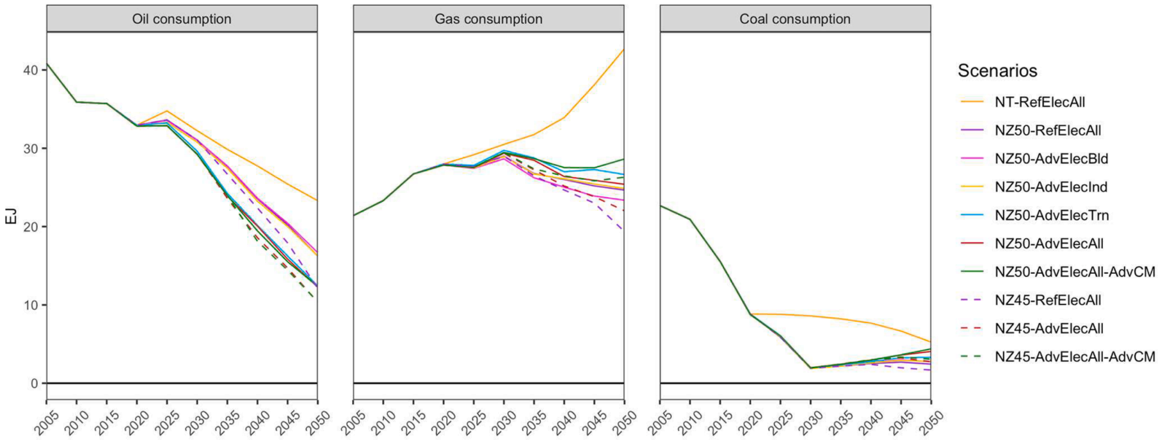

Fig. 8. Domestic fossil fuel consumption. Advanced electrification of all end-use sectors leads to a 24 % reduction in oil consumption in 2050 for scenarios where the United States achieves net-zero CO_2 in 2050 (leftmost panel). Gas consumption remains at a similar level to today's through midcentury in 2050 net-zero CO_2 scenarios with increases in electricity generation and industry offsetting reductions in buildings achieved via electrification (middle panel). Coal consumption falls precipitously in the near term due a full phase out of unabated coal-fired electricity generation by 2030 in net-zero scenarios (rightmost panel).

NZ45-RefElecAll and *NZ45-AdvElecAll* scenarios). In all net-zero scenarios, a phase out of unabated coal-fired electricity generation by 2030 drives a steep decline in coal consumption in the near term (rightmost panel of Fig. 8). Over the longer term, increases in coal consumption are due to the introduction and growth of electricity generation from coal with CCS. Coal consumption in the industry sector does not change considerably in our scenarios prior to 2050 (SI Figure S17).

4. Conclusion

Our results demonstrate that a net-zero transition in the United States will require deep and rapid structural changes to the energy system, from electric power generation to energy use in transportation, industry, and buildings. Specifically, our 2050 and 2045 net-zero CO_2 scenarios clearly show the scale of transformation in the power sector with average annual capacity additions reaching 121-143 GW/year and 172-190 GW/year, respectively, in the 2040s — approximately three to five times the average annual rate of capacity addition from 2021-2023. The magnitude of electricity capacity additions and premature retirements in net-zero scenarios relative to the historical average underscores the scale of the challenges associated with the net-zero transition and point to the need for concerted efforts to establish the required institutional, regulatory, and financial infrastructure. Our results show that advanced electrification of end-use sectors can reduce the magnitude to which negative emissions are relied upon by driving down residual positive emissions by mid-century. Still, CDR through a mix of terrestrial carbon sinks, BECCS, and DACCS is needed to achieve net zero in our net-zero scenarios.

To be consistent with the EMF-37 study protocol, this study models net-zero emissions in terms of CO_2 emissions, enhancing comparability of our study across other studies which are a part of this EMF-37 exercise. Nevertheless, the design is different from the official United States goal of achieving net-zero emissions in terms of economy-wide GHG emissions. Given the challenges associated with reducing some non-CO_2 GHGs, CO_2 emissions from the energy system would need to be net-negative in 2050 in net-zero GHG scenarios [18,31]. And as shown in our 2045 net-zero CO_2 emissions scenarios, this implies even more rapid transitions in the energy system, including more rapid capacity additions, premature retirements, and end-use electrification rates than in our 2050 net-zero CO_2 scenarios. Advanced electrification of end-use sectors in our study is shown to be consistent with lower residual positive emissions by mid-century, which suggests that it may have the potential to aid significantly in helping the United States achieve net-negative CO_2 emissions. Hydrogen is included as a fuel option in GCAM-USA for light-duty vehicles and other industrial energy use, but the version of the model used in this study does not include detailed representation of hydrogen transmission & distribution or the additional hydrogen production updates which were incorporated within O'Rourke et al. [30]. As a common modeling approach, this study uses a top-down national CO_2 emissions constraint to model a net-zero transition for the United States. In reality, the transition will likely be supported by a range of state-, city- and business-level policies and measures [19,37]. Additionally, our study does not include the climate and energy provisions of the IRA [4].

Nevertheless, our study highlights several broad takeaways for policy. Foremost, our results demonstrate a need to establish the infrastructure, policies, and institutions required to facilitate the transition to net-zero. For example, the rapid electrification of the transport sector that is suggested by our scenarios will need to be accompanied by significant increases in the deployment of charging infrastructure throughout the United States. While the rapidly declining battery costs will certainly facilitate rapid adoption of electric vehicles, investments in infrastructure will be essential to sustain that growth. Relatedly, rapid renewable capacity expansion suggests a strong role for storage technologies to accompany the deployment of renewable technologies. Given GCAM's 5-year time steps, further research will be required to better understand storage needs on finer time scales, within the context of the intra-annual, seasonal, and diurnal variation of demand and renewable resources. Our scenarios also suggest a strong role for CDR strategies in a transition toward net-zero emissions. Under a transition toward economy-wide net-zero GHG emissions, the reliance on CDR is likely to be even greater, as evidenced by increased reliance on CDR in our 2045 net-zero CO_2 scenarios. This suggests a strong role for investments in RD&D of CDR strategies — including novel ones beyond those considered in this study [14] — and policies and regulations to deploy those strategies to bring their costs down. Concurrently, a careful consideration of the synergies and tradeoffs of various CDR strategies in combination with broader emission mitigation strategies — including electrification and energy conservation — will be important to minimize the reliance on some CDR strategies such as BECCS that could have negative implications for the food system and natural ecosystems [17]. For example, our study shows that advanced electrification of end-use sectors can lower residual positive emissions, which suggest that it may have the potential to significantly reduce reliance on hitherto nascent CDR strategies.

This study suggests several avenues of future work. First, future studies could explore net-zero transitions for the United States that include existing federal-, state-, city-, and business-level policies and measures explicitly in their analyses. Future work can use the state-level scenarios from this study to conduct more spatially explicit research at the county-scale or more temporally explicit research at seasonal and diurnal scales. Other cost metrics beyond carbon price like household costs or total energy system costs can be useful and can be considered for future work. Our study shows a wide variation in electrification rates across states. Future studies might look at the equity and well-being implications of such transitions in more detail.

Data availability

GCAM is an open-source community model available at https://github.com/JGCRI/gcam-core/releases. A repository containing the modeling files and processed results from our analysis is available at https://zenodo.org/doi/10.5281/zenodo.13693613.

CRediT authorship contribution statement

Kowan T.V. O'Keefe: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Gokul Iyer:** Writing – review & editing, Supervision, Conceptualization. **Kathleen M. Kennedy:** Writing – review & editing, Formal analysis, Conceptualization. **Yang Ou:** Writing – review & editing, Data curation. **Alicia Zhao:** Writing – review & editing, Data curation. **Ryna Cui:** Writing – review & editing. **Haewon McJeon:** Writing – review & editing, Conceptualization. **Nathan Hultman:** Writing – review & editing.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2024.100155.

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