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Evaluating long-term emission impacts of large-scale electric vehicle deployment in the US using a human-Earth systems model

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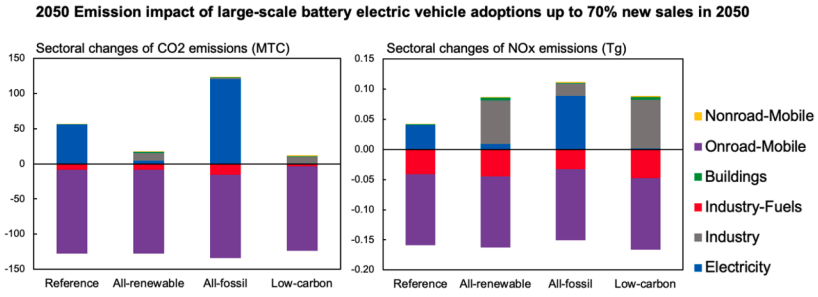
HIGHLIGHTS

- A human-Earth systems model is applied to explore impacts of EVs on emissions.
- Four electric sector pathways are examined out to 2050.
- Net emission impacts are affected by how electricity is produced.
- CO_2 and NO_x emissions decrease through 2050 with additional EVs.
- Coal plant retirement and fuel switching drive $PM_{2.5}$ and SO_2 responses.

GRAPHICAL ABSTRACT



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ABSTRACT

While large-scale adoption of electric vehicles (EVs) globally would reduce carbon dioxide (CO_2) and traditional air pollutant emissions from the transportation sector, emissions from the electric sector, refineries, and potentially other sources would change in response. Here, a multi-sector human-Earth systems model is used to evaluate the net long-term emission implications of large-scale EV adoption in the US over widely differing pathways of the evolution of the electric sector. Our results indicate that high EV adoption would decrease net CO_2 emissions through 2050, even for a scenario where all electric sector capacity additions through 2050 are fossil fuel technologies. Greater net CO_2 reductions would be realized for scenarios that emphasize renewables or decarbonization of electricity production. Net air pollutant emission changes in 2050 are relatively small compared to expected overall decreases from recent levels to 2050. States participating in the Regional Greenhouse Gas Initiative experience greater CO_2 and air pollutant reductions on a percentage basis. These results

Abbreviations: CCS, Carbon capture and storage; CHP, Combined heat and power; CSAPR, Cross-State Air Pollution Rule; EV, Battery electric vehicle; GCAM, Global Change Analysis Model; GCAM-USA, GCAM with a state-level representation of the US energy system; GHG, Greenhouse gas; GREET, Greenhouse gases, Regulated Emissions, and Energy Use in Transportation fuel cycle model; ICE, Internal combustion engine; MOVES, Motor Vehicles Emission Simulator model; NAAQS, National Ambient Air Quality Standards; RGGI, Regional Greenhouse Gas Initiative; USEPA, US Environmental Protection Agency; ZEV, Zero-Emission Vehicle Standards.

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suggest that coordinated, multi-sector planning can greatly enhance the climate and environmental benefits of EVs. Additional factors are identified that influence the net emission impacts of EVs, including the retirement of coal capacity, refinery operations under reduced gasoline demands, and price-induced fuel switching in residential heating and in the industrial sector.

1. Introduction and objectives

Dramatic reductions in battery costs have resulted in battery electric vehicles (EVs) becoming increasingly cost- and range-competitive with traditional passenger vehicle technologies globally [1–3]. EVs are affordable and available to larger segments of the population, and have reached 2% of new sales in the United States (US), 8% in the Netherlands, 7% in Ireland, 3% in Portugal, and 5% in China [4].

The potential for EVs to result in transportation sector emission reductions has led to their inclusion in strategies for mitigating climate change and improving air quality. Governments have used a variety of incentives to increase EV adoption [5,6]. Some examples include point of sale grants (Canada, China, France, Germany, Japan, and the United Kingdom), tax rebates or credits (Norway, the United Kingdom, and the US), relief from taxes and fees (China, France, Japan, the Netherlands, and Norway), and exemptions from limits on registration and driving (China and Mexico).

In the US, California and ten other states have adopted Zero-Emission Vehicle Standards (ZEV), which mandate that EVs attain a specified minimum percentage of passenger vehicle sales [7]. Similarly, twelve states within the Northeast and Mid-Atlantic region of the US have committed to implementing a cap on transportation-sector CO_2 emissions [8]. The federal government and states have also introduced rebates and tax credits to incentivize EV purchases by consumers [9,10].

Influenced by these policies and incentives, EV sales in the US increased by 81% from 2017 to 2018 [11], and approximately 1.2 million EVs were on the road in 2019. While the 2020 Annual Energy Outlook projected that EVs would increase from less than 1% of US passenger vehicle sales in 2017 to 19% in 2050 [12], it is very possible that EV sales could be much higher. The Bloomberg Electric Vehicle Outlook report [13] estimates that EV sales will reach nearly 60% market share in the US by 2040.

Rapid growth of EVs will require an expansion of electricity production capacity to meet the additional demand, and it is well-recognized that clean electricity plays an important role in ensuring life-cycle benefits of EVs [14–16]. Previous bottom-up studies examining the life-cycle emissions of EVs typically have focused on current conditions [17–20] or near-term stylized electric grid mix projections [21–23]. Onat et al. [24] found that EVs could produce unfavorable emission changes based on the current and near-future grid mix in the US. Other studies using life-cycle models have examined longer time horizons, showing increasing benefits through 2030 as the power mix becomes cleaner [25,26]. However, life-cycle models are not readily able to examine potentially important dynamics, such as how the widespread market penetration of EVs could drive electric sector changes, how those changes are also shaped by national and sub-national policies, or how increasing demand for electricity would affect fuel choices in other sectors.

In contrast, energy system optimization models, which select energy technologies and fuels over time to meet societal demands at least cost, are designed to assess cross-sector dynamics and electric sector capacity expansion. Energy optimization models have been used to assess EV market penetration in Japan, India, and the European Union [27–29]. In the US, most applications of such models have evaluated EV impacts at the national or regional scales [30–33] or for a particular state [34,35] or a set of states [36]. A recent study [37] examined transportation emissions scenarios for New York City using a bottom-up energy system optimization model. However, most energy system optimization models do not provide national coverage with state-level resolution. This is a limitation for assessing EV scenarios for the US since many of the policies that shape the response of the electric sector are implemented at the state or regional levels, including the Regional Greenhouse Gas Initiative (RGGI) [38], the Cross-State Air Pollution Rule (CSAPR) [39], and state-specific strategies for meeting National Ambient Air Quality Standards (NAAQS). Thus, while existing studies in the life-cycle and energy system optimization literature have provided valuable insights, considerable uncertainty remains regarding how large-scale EV adoption would affect future net CO_2 and air pollutant emissions.

This study addresses these limitations using the Global Change Analysis Model (GCAM) [40] with a state-level representation of the US energy system (GCAM-USA) [40,41]. GCAM-USA, a multi-sector human-Earth systems model, simulates the evolution of the US state-level energy system over time for scenarios of interest embedded within GCAM's global framework. While a number of previous GCAM applications have focused on energy and emission implications of transportation sector electrification at the global scale [42–46], in other regions [47–49], and in the freight sector [50], this is the first application that evaluates US state-level emission implications of large-scale adoptions of passenger EVs. In this work, emissions changes between low and high EV sales projections are evaluated for four different electric sector pathways, ranging from one in which 100% of new capacity is fossil fuel-based to another in which the electric sector is fully decarbonized by 2050.

This study addresses the following research questions: (1) *What are the system-wide, long-term emission implications of large-scale EV adoption in the US over widely differing pathways of the evolution of the electric sector? and (2) How will future emissions be shaped by the co-evolution of electric sector expansion and end-use demand changes?* While some aspects of these questions have been explored by life cycle analysis and energy system optimization models reviewed above, this study contributes to the growing literature around high EV adoption by using a human-Earth systems model that captures additional multi-sector dynamics. Furthermore, by incorporating representations of key energy and emission policies, this study provides insights into the influence of policy on multi-sector dynamics. These insights are particularly relevant to strategic energy planning and multi-pollutant management. Finally, the strengths and limitations of applying GCAM-USA to assess EV scenarios are demonstrated and potential future research directions are identified.

2. Methods

GCAM has been used to examine scenarios of the future, estimating the associated energy use and impacts on anthropogenic emissions, climate, agriculture, land use, and water. GCAM has 32-region global coverage and a modeling time horizon that spans from 2010 to 2100 in 5-year increments. The model contains comprehensive representations of energy production, transformation, and use, simulating energy technology adoption and tracking energy flows and activity dependencies across economic sectors and regions [51]. For each modeling period, GCAM determines the set of equilibrium prices for agriculture, energy, emission, and policy-related markets that simultaneously balance supply and demand. In contrast to intertemporal energy system optimization models, GCAM employs a dynamic recursive approach that solves each period sequentially, simulating how markets evolve under imperfect foresight.

Building upon GCAM, GCAM-USA disaggregates the US energy system to the state level. GCAM-USA has been applied in US energy system simulations, emission projections, and policy analyses [6,52–56]. In GCAM-USA, energy service demands are estimated based on exogenous

assumptions about population, GDP, and labor productivity at the state level. Market shares of competing technologies are determined using a logit choice function that considers their relative capital, operation and maintenance, and fuel costs [51]. GCAM-USA estimates CO_2 emissions based on fuel use and the carbon content of various fuels. For a specific time period and technology, air pollutant emissions are estimated as the product of an emission coefficient and the quantity of the corresponding economic activity, such as fuel use or service output.

In this application, a version of GCAM-USA v4.3 is modified to include updates to emission factors, implementations of key policies affecting air pollutant emissions, and some degree of calibration to other modeling analyses. Compared with life-cycle models that focus on specific system boundaries and near-term conditions, these policy representations in GCAM-USA can help examine broader and longer-term dynamics. These include the coevolution of fast-growing EV markets and electric capacity expansion, how transportation electrification would affect fuel choices in other end-use sectors, and how those dynamics interact with national and sub-national policies.

In this analysis, national electricity production from coal is harmonized with projections from the Integrated Planning Model through 2050 [57]. Technology-specific emission coefficients for nitrogen oxides (NO_x), sulfur dioxide (SO_2), and directly emitted fine particulate matter ($PM_{2.5}$) are derived from the Argonne Greenhouse gases, Regulated Emissions, and Energy Use in Transportation (GREET) fuel cycle model [58] and from the US Environmental Protection Agency (USEPA) National Emission Inventory and its projections, incorporating existing national and regional air quality, climate, and energy policies [52]. Emission coefficients for passenger and heavy-duty vehicles are obtained from the 2014 USEPA MOtor Vehicles Emission Simulator (MOVES) model [59] and account for Tier 3 vehicle emission and fuel standards as well as the degradation of control equipment over the life of the vehicle [60]. The Tier 3 standards will result in significant emission reductions over time. For example, NO_x emissions per kilometer from new passenger vehicles are expected to decrease 70% from 2010 to 2030 [60].

Emission constraints are applied that reflect the CSAPR and RGGI. CSAPR is a federal rule that places a cap on electric sector NO_x and SO_2 emissions from 23 states. States that have joined RGGI have committed to collectively meeting a regional electric sector greenhouse emissions cap. In this study, RGGI membership includes 11 states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, and Virginia). Pennsylvania has recently announced that it plans to join RGGI but has not yet identified emission reduction targets and is thus not included as a RGGI state here. Since emission caps for CSAPR and RGGI have not been determined beyond 2030, the 2030 caps are held constant through 2050.

Within its transportation sector, GCAM-USA represents four classes of light-duty passenger vehicles: compact cars, midsize cars, large cars, and the combination of light trucks and SUVs. Technologies available within each class include liquid- and natural gas-fueled internal combustion engine (ICE) vehicles, gasoline-electric hybrid vehicles, EVs, and hydrogen fuel-cell vehicles. Plug-in hybrid gasoline-electric vehicles are not explicitly considered in this analysis, but can implicitly be considered as a combination of ICE and EVs.

GCAM-USA does not differentiate between gasoline and diesel fuels, labeling each as “refined liquids”. Ethanol and biodiesel can be blended into the liquid fuel mix. Coal-to-liquids, gas-to-liquids, or cellulosic ethanol production technologies are not included in this study as none of these liquid fuel technologies are currently on the path to achieving broad market share. Similarly, as market trends have not favored natural gas-fueled vehicles, their market share is limited to no more than approximately 2%. These assumptions could be explored further in alternative scenarios.

ICE vehicles are assumed to increase in efficiency through 2025, driven by the Corporate Average Fuel Economy standards [61]. Projected vehicle efficiencies have not been updated to reflect the Safer Affordable Fuel-Efficient vehicles rule [62]. Vehicle cohort lifetimes are modeled with an s-curve such that the maximum lifetime of a vehicle is 30 years, while average lifetimes of passenger cars and trucks are 11.4 and 10.7 years, respectively. These assumptions, which were derived from historic values [63], dictate the speed of fleet turnover. Further details about GCAM and its representation of the transportation sector are provided in Sections 1 and 2 of the Supplemental Information.

In total, eight scenarios are evaluated (Table 1), pairing two levels of EV adoption rates (LO and HI) with four illustrative electric sector pathways (BASE, RNW, FSL, and ESD). These scenarios are built upon common socioeconomic assumptions [64–66] that drive the overall economy and demands of other end-use sectors. The LO EV projections mimic the 2018 Annual Energy Outlook, with EVs accounting for 12% of light-duty vehicle sales in 2050. In the HI scenarios, EV sales shares grow to account for 70% of new passenger vehicle sales in 2050, extrapolated from BNEF’s projection of 60% sales share in 2040 [13] (Table S1).

BASE scenarios allow the electric sector to evolve without additional constraints aside from the aforementioned policies. RNW scenarios assume that all electric sector capacity additions from 2025 forward are from non-biomass renewables (i.e., wind, solar, geothermal, or hydro). In contrast, FSL scenarios require electric sector capacity additions to be fossil fuel technologies (i.e., natural gas, oil, and coal). Finally, ESD scenarios assume the electric sector has fully decarbonized by 2050, a policy goal that has been put forth by several states and that has been identified as being an important component of comprehensive strategies for mitigating greenhouse gases (GHGs) [67]. The decarbonization constraint is implemented by placing state-level caps on electric sector emissions that start in 2020 and decline linearly to zero at 2050. Together, these alternative electric pathways support a bounding analysis, examining the effect of extensive EV adoption over very different electric sector assumptions.

3. Results

3.1. Effects on light-duty travel and electricity production

From 2020 to 2050, total light-duty vehicle service output is projected to increase by approximately 32% (2.4 trillion passenger-km) for the low EV scenarios (BASE-LO, FSL-LO, RNW-LO, and ESD-LO) and 29% (2.2 trillion passenger-km) for the high EV scenarios (BASE-HI, FSL-HI, RNW-HI, and ESD-HI) (Fig. 1a). The high EV scenarios result in greater electricity demands: in 2050, electricity production levels are approximately 16% higher relative to the low EV scenarios. (Fig. 1b). In the high EV scenarios, EVs account for 65% of the total light-duty travel demand in 2050, which is 7 times that of the low EV scenarios (Fig. 1c). Consequently, the transportation sector grows to consume 17–19% of total electricity production by 2050 (Fig. 1d, Table S2).

The incremental changes in sectoral electricity use from 2020 through 2050 indicate that high EV adoption results in the transportation sector being the largest driver of electric sector capacity expansion across all end use sectors (Table 2). BASE-HI has the greatest increase in electricity generation, 7.31 EJ, of which 53% is consumed by the transportation sector. ESD-HI has the lowest incremental electricity generation, 4.34 EJ, of which 88% is associated with EVs. When meeting the high EV adoption goal under ESD, the industry sector decreases its use of electricity by 0.69 EJ from 2020 to 2050, reflecting price-induced

Table 1
Scenario design.

Electric sector pathway	EV market share trajectory	
	Low	High
Base assumptions (BASE)	BASE-LO	BASE-HI
Only fossil fuels from 2025 (FSL)	FSL-LO	FSL-HI
Only non-bio renewables from 2025 (RNW)	RNW-LO	RNW-HI
Electric sector decarbonization by 2050 (ESD)	ESD-LO	ESD-HI

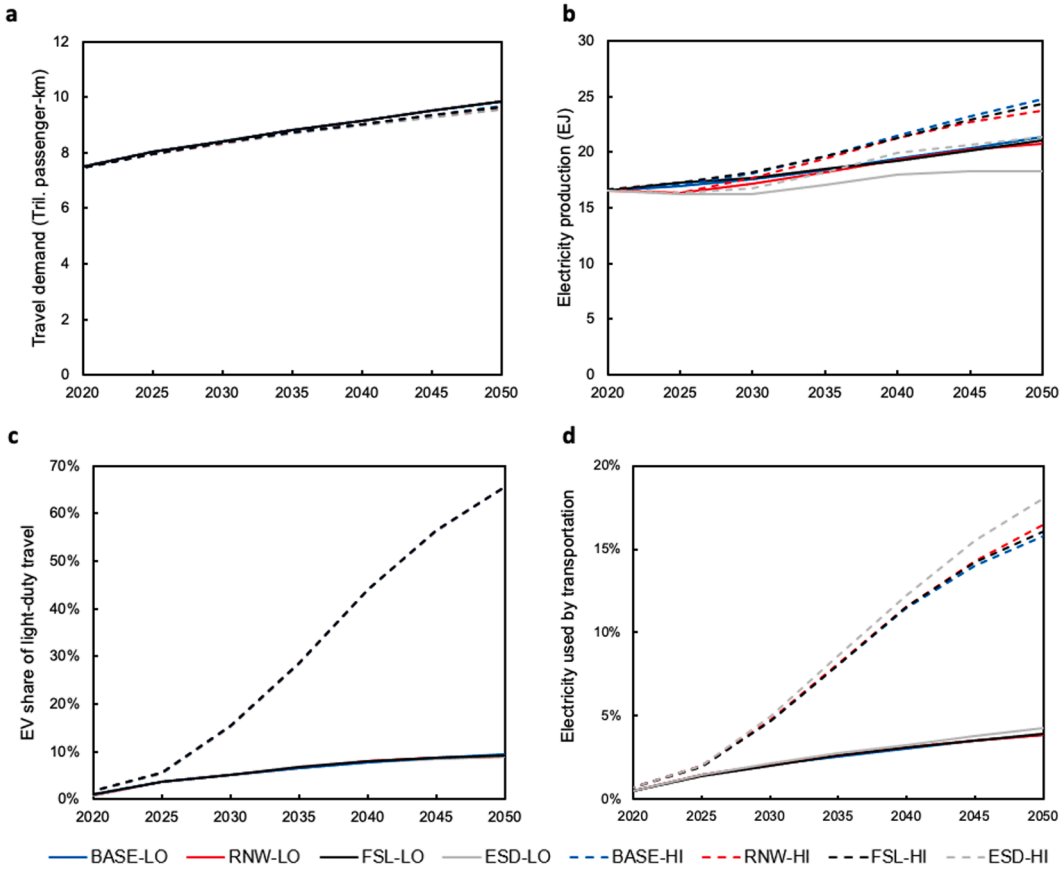

Fig. 1. Summary of light-duty vehicle travel demand and EV shares across eight scenarios. (a) total passenger travel demand, (b) electricity production, (c) EV market share of passenger travel, and (d) the percent of US electricity production that is used in transportation sector. EV refers to the battery electric vehicle (BEV) technology.

Table 2
Increased electricity consumption (EJ) in end-use sectors, 2050 vs. 2020, for each of the high EV scenarios. The percentage of the total increase that is associated with transportation is shown in the last row.

Sector	BASE-HI	FSL-HI	RNW-HI	ESD-HI
Building	1.83	1.72	1.68	1.22
Industry	1.60	1.35	0.84	−0.69
Transportation	3.87	3.87	3.85	3.81
Total increase	7.31	6.94	6.37	4.34
% Transportation	53%	56%	60%	88%

Table 3
Percent changes in the emissions of CO_2 and several air pollutants in 2050 relative to 2020 for scenarios involving combinations of EV levels and alternative electric sector pathways.

	Comparison	BASE	RNW	FSL	ESD
CO_2	2020 to 2050, LO	−11%	−25%	4.7%	−33%
	2050 HI vs. LO	−5.5%	−10%	−1.0%	−10%
	Cumulative, HI vs. LO	−2.0%	−4.0%	−0.11%	−4.1%
NO_x	2020 to 2050, LO	−36%	−37%	−33%	−32%
	2050 HI vs. LO	−2.8%	−1.8%	−0.86%	−1.7%
SO_2	2020 to 2050, LO	−25%	−29%	−17%	−7.8%
	2050 HI vs. LO	1.3%	4.4%	4.2%	3.1%
$PM_{2.5}$	2020 to 2050, LO	−28%	−31%	−22%	−34%
	2050 HI vs. LO	−1.3%	1.0%	1.3%	2.0%

fuel switching.

3.2. *Effects on national CO_2 and air pollutant emissions*

For the four low EV scenarios, net emissions of NO_x, $PM_{2.5}$, and SO_2 are projected to decrease from 2020 to 2050 for all pathways, while CO_2 decreases for all pathways except FSL-LO, a result of its significant fossil fuel capacity additions in the electric sector (Table 3, "2020 to 2050, LO"). Transitioning from low to high EV adoption results in reductions of CO_2 emissions both in 2050 (Table 3, "2050 HI vs. LO") and from 2020 through 2050 (Table 3, "Cumulative, 2020 to 2050, HI vs LO") for all electric sector pathways, although the reductions are minor under FSL. High EV adoption also leads to a small reduction in NO_x in 2050 for all pathways. In contrast, high EV adoption causes $PM_{2.5}$ and SO_2 emissions to increase slightly in 2050.

The overall differences in emissions in 2050 for the high EV adoption scenarios relative to the low EV scenarios can be further decomposed by sector (Fig. 2, Tables S3-S6). For CO_2 (Fig. 2a), reductions from the transportation sector are very similar across pathways. Emissions reductions in the Industry-Fuels category, which includes fuel extraction, processing, refining, and distribution of fuels to all sectors, are also similar across pathways, and are about 10% of the transportation reductions in magnitude. In contrast, differences in electric sector emissions vary greatly by pathway. ESD has a negligible difference, whereas FSL results in an increase that nearly offsets the decreases from Transportation and Industry-Fuel. Emissions from the Industry category, which represents industrial energy use outside of the Industry-Fuels category, increase in RNW and ESD. For these pathways, the combination of increased demand for electricity from EVs and decreased demand for fossil fuels in both the transportation and electric sectors results in fuel switching in the industrial sector, partially offsetting the decreases in the transportation sector.

Sectoral changes in NO_x (Fig. 2b) follow similar trends to those of

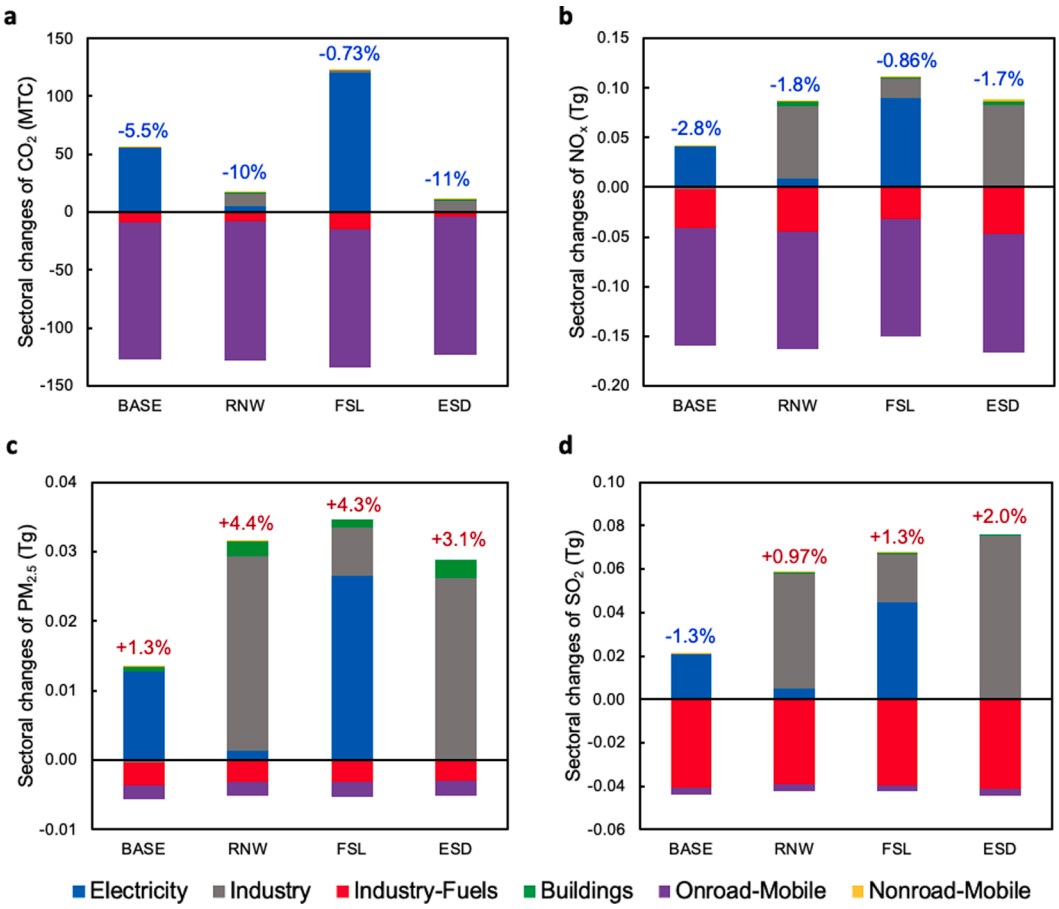

Fig. 2. Sectoral emission changes of HI relative to LO scenarios in 2050 for (a) CO_2, (b) NO_x, (c) direct $PM_{2.5}$, and (d) SO_2 emissions. Percentage at top shows the net change. Industry represents direct emissions from industrial combustion sources (coal, gas, refined liquids, and biomass). Industry-Fuel represents upstream emissions from fuel extraction, processing, refineries, and pipelines.

CO_2, although the relative changes from sector to sector are different. Reductions from Industry-Fuels are nearly one third the reductions from transportation. The increases from the Industry category are greater, particularly for the RNW and ESD pathways. Even a small increase in industrial coal use can impact sectoral air pollutant emissions since the emission factors for coal combustion in the industrial sector are higher than in the electric sector.

For $PM_{2.5}$ (Fig. 2c), net emissions under BASE and FSL grow largely as a result of an increase in electric sector emissions. Fuel switching in the industrial and buildings sectors also plays a major role in overall trends across the other pathways. In the buildings sector, this increase reflects a small increase in residential wood burning, which has a high $PM_{2.5}$ emission factor.

As a result of the Tier 3 sulfur limits on gasoline, displacing gasoline vehicles has only a small impact on 2050 emissions of SO_2 from the transportation sector (Fig. 2d). Instead, changes in Industry-Fuels, Electricity, and Industry drive the response. Again, the results suggest that fuel switching in the industrial sector may play an important role in determining the net SO_2 impact of EVs, particularly in situations where EV market share is sufficient to result in changes in fuel prices.

3.3. Effects of electrification on electricity production

Overall and sectoral emission changes highlight the importance of both the underlying power mixture (Fig. 3a-d) and the technologies that are selected to meet the additional electricity demands of the increased EV market share (Fig. 3e-h). Comparing BASE-HI and BASE-LO, electricity production increases by approximately 3.5 EJ in 2050 (Fig. 3e). Nearly half of the additional generation comes from a combination of coal and gas technologies, with most of the remainder being comprised of wind and solar. Higher coal generation in the BASE-HI scenario results from delayed retirement of a small portion of coal capacity, which is retained to meet increased electricity demands, rather than from the addition of new coal capacity. Incremental electricity production for the RNW and FSL scenarios (Fig. 3f-g) reflects the underlying constraints of those scenarios. Capacity additions under ESD (Fig. 3h) are similar to RNW (Fig. 3f), but exhibit slightly different quantities of solar, wind, gas, as well as combined heat and power (CHP) because GCAM-USA seeks to meet additional electricity demands under the decarbonization constraint.

The CO_2 emission intensity of electricity through time provides additional insights into the electric sector response (Fig. 4). In BASE-LO, RNW-LO, and ESD-LO, the CO_2 intensity of electricity declines steadily over time. Adding high EV market penetration decreases the intensity further, indicating that capacity additions to meet EV electricity demands are lower in emissions intensity than the existing stock otherwise would be. In contrast, CO_2 intensity for FSL-LO increases slightly over time, and the intensity increases further as all capacity additions are required to be coal or gas.

3.4. Effects on regional emission trends

The state-level resolution of GCAM-USA provides additional insights on how the response to high EV adoption varies regionally. Here, state-level emissions are aggregated to the US Census Division level to examine regional trends (Table 4) (see Fig. S1 for a map of the Census Divisions). The New England region has much larger reductions in CO_2 (16%) than other regions, which range from 3.0% (East North Central)

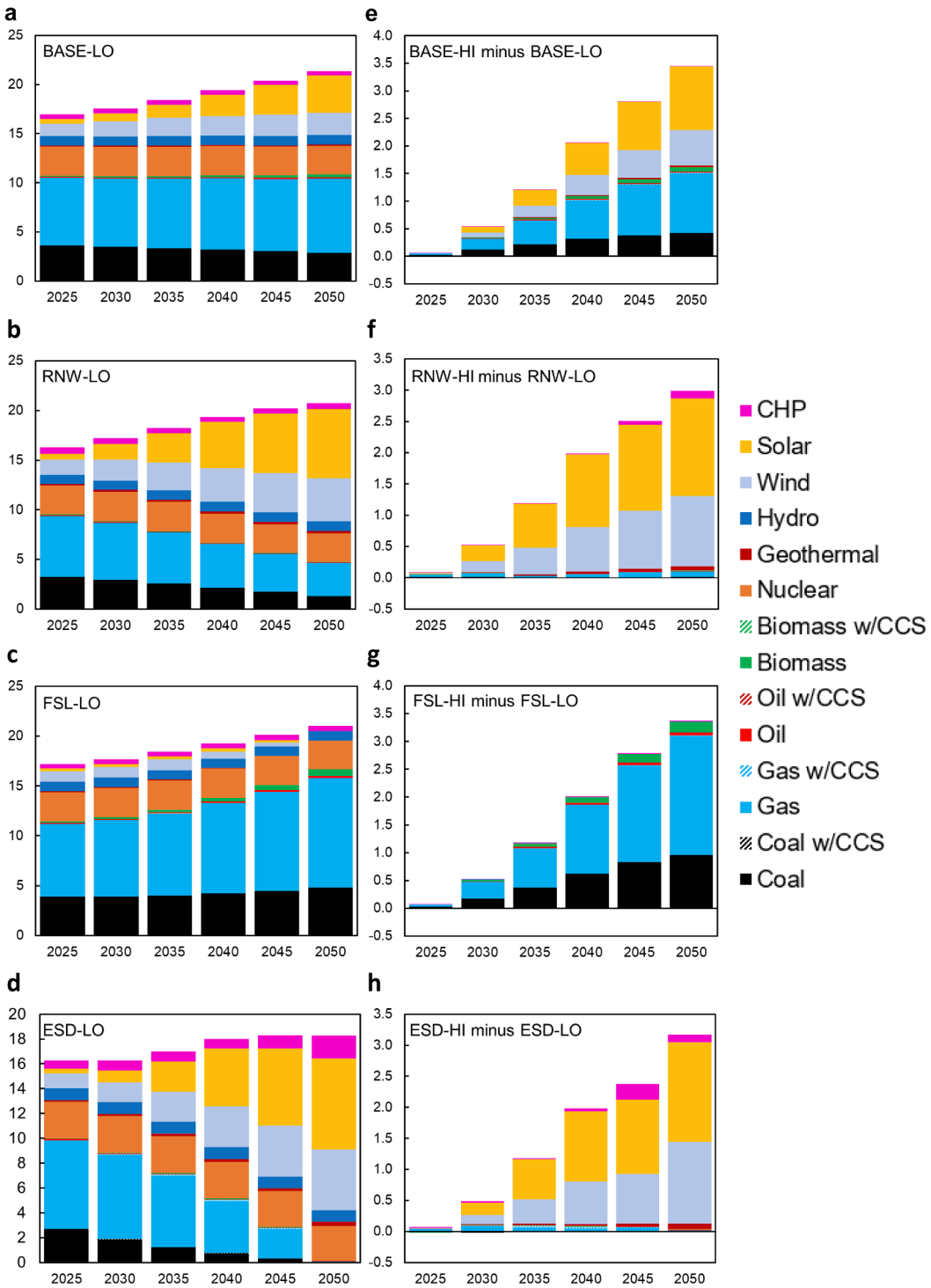

Fig. 3. US electricity production by fuel (EJ) for each of the low EV scenarios (a-d), as well as increases in electricity production in HI relative to LO by technology in their corresponding higher EV scenarios (e-h).

to 8.8% (South Atlantic). New England also has the largest percentage reduction of NO_x (4.5%). These regional trends are similar for other electric sector pathways (Table S7-S9). For example, New England also has the largest relative CO_2 reductions under RNW (19%), FSL (11%), and ESD (21%), demonstrating the robustness of the benefits of widespread EV adoption in New England across widely varying assumptions for the evolution of the electric sector.

Other regional trends are evident in Table 4. In BASE, SO_2 emissions changes range from an increase of 1.4% in the South Atlantic to a decrease of 6.6% in the Pacific. In contrast, $PM_{2.5}$ emissions increase in all regions and nationally, although the largest increases are in the Mountain (2.3%) and East South Central (2.1%) Census Divisions.

The benefits in New England, Middle Atlantic, and Southern Atlantic regions are partially driven by RGGI (see Fig. S2 for a map of states included in RGGI). Within the RGGI region, CO_2 emissions are reduced by 14%, NO_x by 4.8%, and SO_2 by 5.0% for BASE. While $PM_{2.5}$ emissions increase, this increase is small relative to increases in other regions. The dynamics of the regional CO_2 cap are driving these responses. Increasing EV demands for electricity are met in BASE by retiring additional coal capacity while deploying more renewable and natural gas capacity

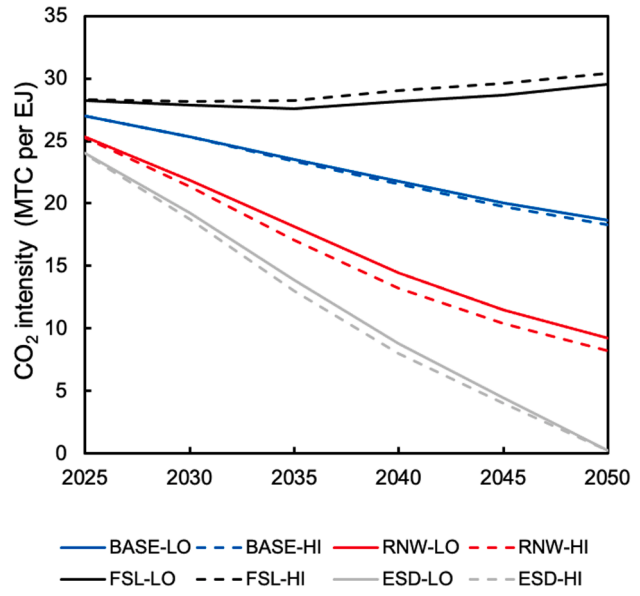

Fig. 4. CO_2 intensity (MTC per EJ production) of electricity production across eight scenarios.

Table 4
Percent changes in regional CO_2 and select air pollutant emissions in 2050 between low and high EV scenarios under BASE electric sector assumptions. National totals include emissions from fuel extraction and processing that are not allocated to states by GCAM-USA.

Region	CO_2	NO_x	$PM_{2.5}$	SO_2
New England	−16%	−4.5%	0.76%	−2.5%
Mid-Atlantic	−6.7%	−3.2%	1.7%	−1.0%
East North Central	−3.0%	−1.9%	1.4%	−0.11%
West North Central	−4.4%	−2.4%	0.69%	0.29%
South Atlantic	−8.8%	−2.8%	1.6%	1.4%
East South Central	−4.4%	−2.3%	2.1%	0.40%
West South Central	−3.8%	−3.2%	0.64%	−4.7%
Mountain	−3.8%	−2.2%	2.3%	0.43%
Pacific	−7.9%	−4.2%	1.0%	−6.6%
RGGI states*	−14%	−4.8%	0.30%	−5.0%
National	−5.5%	−2.8%	1.3%	−1.3%

* RGGI states are CT, DE, MA, MD, ME, NH, NJ, NY, RI, VA, and VT.

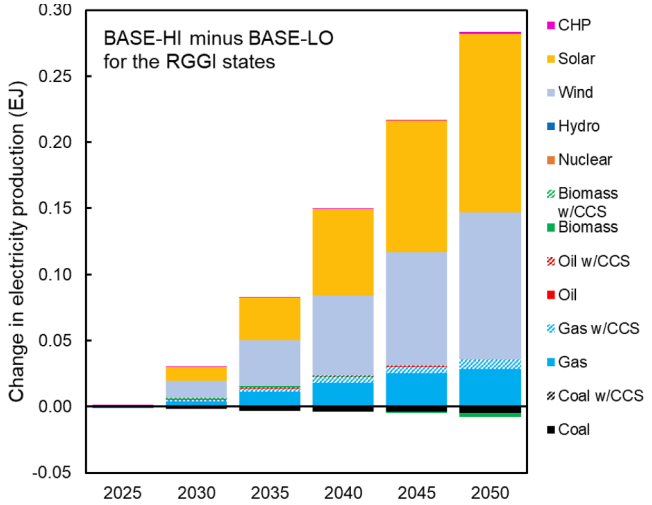

Fig. 5. Change in electricity production by fuel for the RGGI states in BASE-HI relative to BASE-LO.

(Fig. 5, Fig. S3). Coal retirement results in the co-benefit of reductions in NO_x and SO_2 (Fig. S4a-d). The results indicate the potential for $PM_{2.5}$ emissions in the RGGI states to increase, driven by an increase in residential wood heating and by industrial fuel-switching.

4. Discussion

This work explores the system-wide emission implications of unprecedented - but increasingly plausible - scenarios in which large-scale EV adoption is the largest driver of the future power expansion. Use of a human-Earth systems model facilitates an examination of interactions and synergies between the transportation and electric power sectors, including the potential role of policies such as RGGI in shaping these interactions. Results suggest that relatively small net CO_2 and air pollutant emission changes in 2050 would occur due to high EV adoption compared to the overall decreases from recent levels to 2050 that are expected to occur in the US. Nevertheless, a major increase in EV market share results in further national and regional emission reductions of CO_2 and NO_x through 2050 in BASE and in each of the alternative electricity production pathways that were explored. Even under a hypothetical scenario in which all new capacity additions are fossil fuel (FSL), greatly expanded EV deployment does not lead to an increase in CO_2 and NO_x emissions in 2050.

The robust emission benefits from greater EV adoption across wide-ranging electric power generation pathways are generally consistent with the findings of studies that focus on other regions. For example, Knobloch et al. [68] conclude that electric cars are less emission intensive than fossil-fuel-based alternatives in 53 global regions and achieve net emission benefits even under a moderate rate of power-sector decarbonization. Schnell et al. [69] find consistent improvements in air quality and greenhouse gas reductions from light-duty vehicles electrification in China regardless of power generation source. However, our results also suggest high EV market share could lead to slightly higher $PM_{2.5}$ and SO_2 in 2050 nationally and in most regions relative to the low-EV scenarios. These disbenefits are mostly attributable to the delayed retirement of existing coal plants and to fuel-switching in other sectors, particularly in residential heating and industrial fuel combustion.

An interesting observation is the importance of fuel switching in the Industry sector on the net emissions impacts of EVs, especially for the ESD and RNW pathways. Here, Industry represents direct emissions from industrial fuel combustion (coal, gas, and refined liquids), which is different from the upstream emissions in the Industry-Fuel category. For RNW and ESD, GCAM-USA projects an increase in industrial sector fossil fuel use. While such a real-world response may be possible, it should be noted that GCAM-USA currently does not explicitly represent any technology-specific (real-world) constraints in this sector. As a result, the increased industrial emissions from fuel-switching under these pathways are likely overestimated.

This study contributes to the growing literature involving US state-level energy system modeling and emission projections using integrated human-Earth systems models. Specifically, results suggest that regional policies can be a major factor in driving the benefits of EVs. For example, a regional cap on CO_2 emissions amplifies benefits, as percent reductions of CO_2 and traditional air pollutant emissions are among the largest for the RGGI states. As electricity demands increase, RGGI not only decreases the carbon intensity of capacity additions, but also accelerates the retirement of existing coal capacity. Here, the implementation of the RGGI cap holds the regional CO_2 constraint constant from 2030 through 2050. If RGGI becomes more stringent over time and expands to more states, such as Pennsylvania and North Carolina, the benefits of vehicle electrification in the RGGI states could increase. These results illustrate the importance of coordinated transportation and regional electric sector planning for achieving long-term emission reduction goals. Note that RGGI imposes a mass-based cap in which regional electric sector CO_2 emissions cannot exceed a specified

tonnage. Emission policies can alternatively be implemented as rate-based caps, limiting the emissions per unit of electricity produced. For scenarios involving large-scale EV market penetration, rate-based caps may not be as effective in driving GHG reductions and air pollutant co-benefits.

The results are influenced by dynamics that would benefit from additional exploration. Such dynamics could include the response of refinery activity to reduced demand for gasoline, increased use of biomass in residential heating, an increased role for CHP, retirement of existing electricity production capacity, and factors influencing electric sector capacity expansion and retirement. For example, the version of GCAM-USA used in this study represents annualized supply and demand for electricity and is not able to capture the effects of dispatch decisions on retirement. In practice, expansion of solar power can result in a shift of a portion of coal capacity from baseload generation to load-following, affecting its cost-effectiveness [70]. Furthermore, variable electricity demand due to charging electric vehicles may increase the competitiveness of flexible electricity generation options that can ramp quickly, such as natural gas or hydropower in certain regions. Given the importance of fuel switching in the industrial sector in several of the scenarios, a more detailed analysis of this sector is warranted given the aggregated nature of the industrial sector in GCAM-USA. The results also indicate that the emissions implications of EVs can differ from one part of the country to another, and more fully exploring the drivers behind those differences could provide insights regarding the efficacy of EVs in achieving emission goals from a state or regional planning perspective.

It should be noted that this integrated modeling framework has some structural limitations compared with some bottom-up, process-based models used in EV studies. For example, GCAM-USA currently does not simulate important intra-annual and intra-day dynamics. Such dynamics could have an impact on dispatch, retirement, and capacity expansion in the electric sector, as well as the ability to analyze alternative EV charging patterns. Another limitation is the simplified representation of the electricity transmission, which does not fully capture regional electricity trade, transmission bottlenecks, and the possibility for vehicle-to-grid applications of EVs as energy storage systems. Note that many of these limitations are being actively addressed in ongoing GCAM model development activities. Furthermore, while this study focuses on light-duty passenger vehicles as their market share has been growing rapidly in recent years, future work could explore emerging electrification in the commercial vehicle and heavy-duty vehicle sectors. Future EV scenarios would also benefit from improved representation of technology innovation and diffusion, such as harmonization of battery cost reductions in EVs and stationary energy storage, the use of end-of-life vehicle batteries in stationary storage applications, and consumer behavior.

One possible direction for considering some of these various details is to couple GCAM-USA with more detailed process- and sector-based models. For example, GCAM-USA electricity demands could be evaluated in more detail using an electric sector model that specializes in issues such as capacity expansion, dispatch, and transmission. GCAM-USA could also be linked to life-cycle analysis models, which could extend the analysis to include the emissions associated with manufacturing various energy system technologies, such as vehicles, boilers, and wind turbines.

5. Conclusions

A human-Earth systems model, GCAM-USA, is applied to evaluate the impacts of widespread EV adoption under alternative pathways for electric sector evolution in the US. This approach was able to provide a holistic assessment of emission changes, including those in the transportation, electric, refinery, and fuel production sectors. It also accounted for important dynamics, such as capacity expansion in the electric sector and fuel switching across sectors in response to changes in energy prices. By highlighting the importance of alternative electric sector pathways, state-level policies, and cross-sector interactions, our results support the utility of using such a framework to analyze EVs.

GCAM-USA indicates that widespread EV adoption generally would reduce CO_2 and NO_x emissions, and that these responses are robust across electric sector expansion pathways. Despite their smaller magnitude compared with the overall decreases from 2020 to 2050, achieving additional CO_2 and NO_x reductions is important for addressing climate change and air pollution. While the reductions of each (0.24–11% of CO_2 and 0.06–2.8% of NO_x in 2050) were relatively modest, the scenarios that were evaluated only considered electrification of light-duty vehicles. Similar to Milovanoff et al. [71], the results indicate that light-duty electrification alone is not the solution to climate and air quality concerns, but it could play an important part of a larger strategy.

While delayed retirement of coal plants and industrial fuel switching result in some disbenefits for direct $PM_{2.5}$ and SO_2 emissions, these disbenefits are small relative to expected future reductions. Dynamics associated with dispatch and an increasing load-following role for coal, which are not captured in this study, may result in additional coal plant retirements. Future versions of GCAM-USA are expected to include load segmentation and electricity dispatch [54], potentially improving the ability to represent retirement decisions. Earlier coal retirements would likely decrease $PM_{2.5}$ and SO_2 emissions, countering the disbenefits observed in this study.

While this paper highlights some limitations associated with modeling EVs within GCAM-USA, many of these limitations are being addressed through ongoing model improvements. Such efforts are adding technological detail to the industrial sector and allowing greater operational flexibility in the electric sector of GCAM-USA. Some limitations can also be addressed by linking GCAM-USA to more detailed process-based models. As these developments are realized, policymakers will be better able to anticipate the role that vehicle electrification can play in meeting environmental and climate goals, as well as the relative efficacy of EVs and alternatives such as energy efficiency, renewable fuels, and other end-use electrification strategies.

Finally, although this study is focused on the US, similar approaches could be applied to examine the impacts of large-scale EV adoption for other countries or regions. For example, electrification of the transportation sector is likely to be an integral component of achieving China's recent net-zero commitment by 2060 [72] and the European Union's 2050 climate neutrality pledge [73], and it is important to consider the multi-sector dynamics that will accompany such a broad transformation. Like the US, both the EU and China are also heterogeneous, with differentiated electric sector composition, access to renewable resources, and policies. Technology-rich integrated assessment models with state or province-level resolution, such as GCAM, could potentially support long-term, integrated climate, energy, and air quality management in those countries as well.

Disclaimer

The authors declare they have no competing interests. The views expressed in this article are those of the authors, and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency, Pacific Northwest National Laboratories, and the University of North Carolina at Chapel Hill. Mention of organization names and trademarks does not constitute endorsement.

Data availability

Data used to perform this study can be found in the Supplementary Information. Supplementary Data, including that used in figures, is publicly available (http://doi.org/10.23719/1519404), as are the source code and executable for GCAM-USA version 4.3 (https://github.com/JGCRI/gcam-core/releases). The full set of GCAM-USA input files required to perform this study is available from the corresponding

author upon request.

CRediT authorship contribution statement

Yang Ou: Conceptualization, Methodology, Writing - original draft. **Noah Kittner:** Conceptualization, Writing - review & editing. **Samaneh Babaee:** Data curation. **Steve J. Smith:** Writing - review & editing. **Christopher G. Nolte:** Writing - review & editing, Project administration. **Daniel H. Loughlin:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Project administration.

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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2021.117364.

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