

# State-led climate action can cut emissions at near-federal costs but favors different technologies

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Gavin Mouat<sup>1</sup>, Christopher Galik<sup>2</sup>, Aranya Venkatesh<sup>3,4</sup>, Katherine Jordan<sup>3,5</sup>, Aditya Sinha<sup>1,6</sup>, Paulina Jaramillo<sup>3</sup> & Jeremiah X. Johnson<sup>1</sup> ✉

In the absence of comprehensive federal greenhouse gas mitigation policy, state-led strategies may play a pivotal role, particularly following the 2024 United States presidential election. Using a detailed energy system optimization model, we examine the outcomes of 23 climate-minded states pursuing net-zero emissions targets compared to a federal carbon cap achieving equivalent CO<sub>2</sub>-eq reductions. Here we show that state-led decarbonization results in distinct technology choices, a 0.7% increase in system costs, and nationwide emissions reduction of 46% – substantial, but insufficient for ambitious climate goals. This pathway relies more on electrification, with 952 terawatt-hours more generation in 2050, reallocating 17.2% of emissions to the power sector. Some regions favor solar, wind, and storage, while direct air capture emerges as critical, particularly in California and the Northeast. Inter-regional trading supports and complicates mitigation efforts, underscoring the need for careful policy design. Overall, our findings highlight how state-led and federal decarbonization approaches can yield differing energy portfolios to achieve similar emissions reductions.

As member countries undergo annual emissions stocktakes and the Trump Administration moves to withdraw from the Paris Climate Agreement, greenhouse gas (GHG) reductions continue to fall short of levels necessary to meet radiative forcing goals<sup>1,2</sup>. The 2023 United Nations Framework Convention on Climate Change (UNFCCC) synthesis report updates the Nationally Determined Contributions (NDCs) of engaged parties and estimates 2030 emissions will be 8.8% higher than 2010 levels<sup>3</sup>. Between the 2022 and 2023 reports, 2030 emissions growth estimates dropped 1.8% from 10.6%. While this diminishing rate of emissions growth is promising, it fails to achieve the most transformative global targets.

The Biden Administration set the United States' contribution to this goal at an ambitious 50% reduction in GHG emissions from 2005 levels by 2030<sup>4</sup>. In comparison to global trajectories, the United States achieved an 18% reduction from 2005 levels in 2021, indicating

progress toward this goal<sup>5</sup>. The 2022 Inflation Reduction Act (IRA) bolstered mitigation efforts, serving as one of the nation's largest ever federal laws providing grant and loan support for clean energy technologies. However, while the Biden Administration's support for deep decarbonization was high, further federal action in the near-term is unlikely, and analysis suggests that the IRA alone is insufficient to meet the U.S. NDC targets<sup>6–9</sup>. Furthermore, the Trump Administration operates in stark contrast, with a core tenet of introduced Executive Orders being to curtail “government overreach.”<sup>10</sup> Though the impacts of Trump's rollbacks are debated in their severity<sup>10–14</sup>, these divergent approaches across administrations illustrate the extent to which federal action on climate change is volatile and may shift abruptly with changes in administration.

Trump's 2024 reelection, compounded by an increase in gridlock and polarization of Congress<sup>15,16</sup>, raises doubt as to both the durability

<sup>1</sup>Civil, Construction & Environmental Engineering, North Carolina State University, Raleigh, NC, USA. <sup>2</sup>School of Public and International Affairs, North Carolina State University, Raleigh, NC, USA. <sup>3</sup>Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, USA. <sup>4</sup>Present address: EPRI, Palo Alto, CA, USA. <sup>5</sup>Present address: Toyota Research Institute, Los Altos, CA, USA. <sup>6</sup>Present address: RTI International, Durham, NC, USA. ✉e-mail: [jjohns24@ncsu.edu](mailto:jjohns24@ncsu.edu)

and the prospect for expansion of climate or energy legislation through the federal pipeline. In the short term and when considering the risk of carbon lock-in, one can argue that the federal government must be framed as fragmented, and perhaps supplementary to the states, when contemplating the United States' energy transition. In contrast to the uncertainty of federal support, over two-thirds of the American public now believe the United States should prioritize developing alternative energy sources<sup>17</sup>. The urgency of climate projections, the risk of technological lock-in, and strong citizen support thus turn the current question from when we will decarbonize to how.

As of late, the answer to this appears to stem from the concept of climate federalism within the policy literature. Climate federalism arose as an academic subject of interest in the United States in the early 21st century. As many recognized the weaknesses of top-down approaches (e.g., Kyoto Protocol), there was concurrent recognition of the subnational diffusion of climate governance. In 2023, twenty-four states plus the District of Columbia had specific adopted GHG emission targets<sup>18</sup>. State-level climate and energy legislation has grown over the last decade, and academic interest in environmental policy at the state level is nearly at a 30-year peak<sup>19</sup>. A rationale for this diffusion of energy and climate policy to subnational groups is that they may use their institutional capacities in more effective ways than the previously postulated top-down thinking. Often, to gain a competitive advantage, it is not uncommon for states to take early action<sup>20</sup>. Barry Rabe addressed the benefit states may get from a head-start on climate legislation, quoting a 2007 address to the General Assembly where Pennsylvania Governor Edward Rendell said, "I believe renewable energy will dominate the economy of the next two decades...For too long, Pennsylvania has been held back because so much of our employment was in industries that were shrinking. But with renewable energy, we have a chance to be a leader in one of the fastest-growing segments of this new economy. We should jump at the chance."<sup>20</sup> Speaking directly to these trends, Rabe further coined the term "contested federalism," in which high federal and state involvement may simultaneously occur. The contested element of this behavior arises from the potential conflict of objectives which may occur between the federal and state level, with early examples including the divisive *Massachusetts v. EPA* 2007 ruling.

Based on the potential for subnational climate leadership, we ask in this research: As compared to federal action, what are the technology and cost implications of state-led decarbonization efforts? To answer this question, we conduct a two-scenario modeling exercise using a comprehensive energy system optimization model (ESOM). The initial scenario, termed State Action, considers the political potential of each U.S. state to enact a mid-century net-zero emissions goal. This by-state assessment is then used to generate a regionally variable emissions reduction plan, divided via the ESOM's nine preset regions. Following the execution of the by-state first scenario, resultant emissions are used as a homogeneous, nationwide emissions constraint for the second scenario (National Action). The intention of this study is to elucidate differences in technology deployment and system-wide cost arising from shifting emissions constraints from heterogeneous (by-state) to homogeneous (nationwide). It is important to note that because only a subset of the states would be included as net-zero policy participants, neither scenario would achieve nationwide net-zero emissions by mid-century. These results, however, will shed light on how a singular goal – namely the reduction of greenhouse gas emissions – could be pursued and achieved (or partially achieved) at different administrative levels, but at different costs and technology choices as driven by local resource availability and other constraints.

Energy system optimization models have emerged as the pre-dominant model type for energy systems analysis over the past decade<sup>21</sup>. This prevalence is attributed to the unique analytical

advantages inherent in ESOMs, particularly their robust technological representation. Often designed with the primary objective of cost minimization, these models excel in optimizing both investment and operational decisions while facilitating the endogenous selection of highly detailed technologies in some instances. Recent applications of ESOMs in the context of decarbonization literature reveal their widespread utilization in nationwide, multi-sectoral decarbonization pathway analyses<sup>21</sup>. At a high level, ESOMs hold significant appeal in decarbonization research due to their ability to address all three components of the energy trilemma. These models, characterized by their ability to reflect least-cost system design (affordability), constraints on greenhouse gases and other pollutants (sustainability), and meeting exogenously-specified energy demands (security), make them particularly attractive for policymakers. This appeal forms the basis for their selection in the present paper.

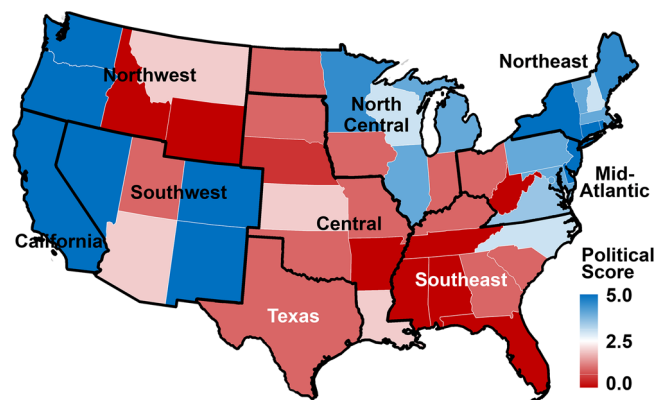
Despite the extensive use of these models in decarbonization studies and for decision-making, there exists little research specific to a state-led U.S. energy transition. Integrated Assessment Models (IAMs) serve as a common alternative to ESOMs, offering broader coverage across modeled sectors at the expense of detailed technological representation. These models are widely utilized for research inquiries similar to ours. Using the IAM GCAM-USA, authors Hultman et al. explore the expanding role of subnational entities in U.S. decarbonization until 2030. Aggregating commitments from subnational emissions reduction efforts such as the coalition *We Are Still In*, Hultman finds current binding commitments yield a 25% reduction in U.S. emissions by 2030. Two additional scenarios, one bolstering current subnational commitments and the other enhancing both subnational and federal commitments in tandem, yielded 37% and 49% decarbonization by 2030, respectively<sup>22</sup>. Though not directly investigating a federalist decarbonization, Zhu et al. uses US-TIMES to integrate "politically feasible" policy portfolios into a techno-economic decarbonization analysis<sup>23</sup>. They create three political scenarios of varying federal climate policy alignment based on the political party of the president and congressional majority. Estimations of emissions reduction potential for these scenarios ranged from 24% to 44% by mid-century. Of note in this study was the sectoral competition between the building and transport sectors for clean electricity, as well as the lack of policies represented in the industrial sector.

In Peng et al., the authors use GCAM-USA to analyze the impact of heterogeneous climate policy on U.S. decarbonization. To do this, they proxy by-state climate policy as a carbon tax, scaled by citizen support. Low-involvement states had a carbon tax roughly one-third that of high-involvement states. Exploring uniform versus heterogeneous decarbonization scenarios of 20, 40, 60, and 80% emissions reduction, the study finds that the heterogeneous scenarios consistently cost within 10% of their uniform counterparts. Under their carbon tax design, they assert that federalist approaches could be more viable, with higher costs borne by states with residents most politically willing to pay for emissions reductions<sup>18</sup>. While Peng et al. examine heterogeneous decarbonization through emissions reduction constraints, lesser insight is provided on the nuances of capacity expansion and technology deployments.

In this work, we use the energy system optimization model Temoa to explore the technology and cost implications of state-led versus federal-led decarbonization strategies in the United States, identifying context-specific technology choices required for state-led decarbonization. We find that state-led approaches yield heterogeneous technology deployments, with increased reliance on electrification, regional expansion of renewable energy and battery storage, and a critical role for direct air capture in achieving emissions reductions. Despite these differences, the cost increase compared to the federal scenario for equivalent emissions reductions is small. Our findings highlight how shifting from uniform national policies to a state-led framework reshapes energy system outcomes, offering insights into

**Table 1 | Political Indicator Inventory**

Indicator	Scale	Scale Point Assignment
Renewable Portfolio/Clean Energy Standard	[0, 1]	0 if not present, 1 if present
Greenhouse Gas Reduction Goal	[0, 1]	0 if not present, 1 if present
2020 Governor Affiliation	[0, 1]	0 if Republican, 1 if Democratic
2020 Legislative Majority	[0, 0.5, 1.0]	0 if Republican, 0.5 if split, 1 if Democratic
2020 Governor Vote	[0, 1]	0 if Republican, 1 if Democratic
2020 Presidential Vote	[0, 0.5, 1.0]	0 if Republican, 0.5 if split, 1 if Democratic



**Fig. 1 | Political score used to identify net-zero ambition states.** States shaded blue are included as net-zero states in the State Action scenario, while those shaded red are excluded. State map obtained via Creative Commons license<sup>44</sup> and modified using Adobe Photoshop.

the opportunities and challenges of achieving net-zero targets under a climate federalism paradigm.

## Results

### Policy scenario design

Within this analysis, we are not modeling to see which policies are most effective at decarbonizing the United States economy. Instead, we are looking at the impact of governance level on decarbonization strategy and technology choice. As a result, the State Action scenario aims to identify and capture the aggregate emissions reduction of states that possess general political potential for mid-century deep decarbonization. It should be noted that this is not an exhaustive exploration of the subnational decarbonization policy space, but rather an exploration of how state-level emissions targets may be realized in the future. For states identified as most amenable to climate policy, we introduce a CO<sub>2</sub>-eq emissions constraint that linearly decreases until net-zero CO<sub>2</sub>-eq emissions in the energy sector are achieved in 2050. This approach is representative of the array of carbon cap policies frequently considered in decarbonization scenarios.

We identify potential net-zero states using a set of five political indicators (Table 1): the adoption of a state-level Renewable Portfolio Standard/Clean Energy Standard, a greenhouse gas reduction goal, the political affiliation of the governor and legislative majority, and the presidential vote<sup>24</sup>. The selection of these political indicators follows existing policy literature identifying liberal citizen ideology and partisan control of the legislature as strong drivers of climate and energy policy adoption. The additional combination of examining both existing climate and energy policy, as well as political partisan makeup, further strengthens this selection. With a maximum possible score of five, a score of at least 3.0 is set as the binary threshold for states with

**Table 2 | Regional Clustering by State Action Scenario Decarbonization Constraint & Realized Emissions Reductions**

Net-Zero Potential	Regions Included	Share of 2019 Emissions Under Net-Zero Plan	Actual Reduction, State Action	Actual Reduction, National Action
<b>High</b>	California	100%	100%	62.90%
	Northeast	100%	100%	36.00%
<b>Mixed</b>	North Central	63.90%	65.10%	41.60%
	Mid-Atlantic	63.60%	62.90%	51.00%
	Northwest	53.10%	46.90%	37.70%
	Southwest	54.20%	40.40%	55.00%
<b>Low</b>	Southeast	13.10%	9.90%	53.30%
	Texas	0.00%	9.80%	29.50%
	Central	0.00%	1.60%	40.30%

predicted mid-century net-zero involvement. Those at or above this score were deemed net-zero states, those below had no added carbon constraint. Based on these criteria, 23 states and the District of Columbia are included as net-zero states, shown in Fig. 1<sup>25</sup>. These selection criteria and the resulting net-zero states are consistent with the set of states identified as highly involved in climate legislation in robust state-level policy trackers such as Climate X Change<sup>26</sup>. All selected net-zero states in our analysis have 16 or more climate policies enacted, as identified by Climate X Change, while all other states have 10 or fewer such policies enacted. We acknowledge that there is no single correct set of net-zero states, as the enactment of any policy is subject to uncertain passage. In addition, the composition of this group of states is likely to change over time in response to evolving political dynamics, shifts in citizen preferences, and the broader policy landscape. We also note the 23 selected states include all of the states that currently have binding net-zero commitments – California, Colorado, Maryland, Massachusetts, New York, and Rhode Island<sup>27</sup>.

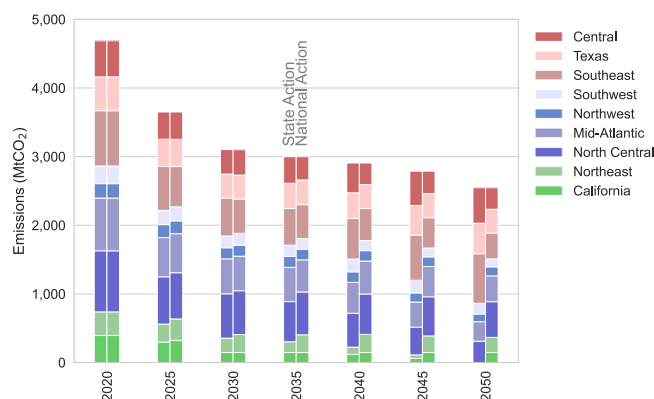
Initial CO<sub>2</sub>-eq emissions rates were then obtained from the Energy Information Administration and used for the 2020 model base year<sup>28</sup>. We then assigned unique CO<sub>2</sub>-eq emissions constraints to each of the nine Temoa model regions based on the presence of net-zero states and their 2020 baseline emissions. Since our approach groups states into regions that largely align with power system balancing authority boundaries, emissions are also aggregated regionally, with reductions proportional to net-zero participation. For example, North Carolina was the only state in the Southeast region to be classified as a net-zero state in the State Action scenario. As such, Southeastern emissions were constrained to eliminate North Carolina's share of emissions starting at 2020 levels until reaching net-zero in 2050. This was done for regions with partial net-zero participation.

In addition to these emissions constraints, both scenarios have baseline policies that existed at the end of 2022, including state-level Renewable Portfolio Standards (RPS), the Cross-State Air Pollution Rule (CSAPR), the California Cap and Trade Program, the federal Investment Tax Credit, and provisions of the Inflation Reduction Act. They are assumed to remain in their current form.

### Scenario emissions reductions

Mid-century regional CO<sub>2</sub>-eq emissions constraints for the State Action scenario ranged from 0% to 100%, as presented in Table 2. Emissions limits are on a production-basis rather than consumption. Implementation of these constraints in a Temoa model run yielded resultant regional emissions reductions from 1.6% (Central) to 100% (California & Northeast) in 2050. To aid in the interpretation of results, we categorize regions into High, Mixed, and Low involvement, based upon

their likelihood to seek complete, partial, or little to no decarbonization by mid-century within the State Action scenario. Overall, the State Action scenario yielded a 45.7% nationwide CO<sub>2</sub>-eq emissions reduction, displayed in the left bars of Fig. 2. Given that the National Action scenario used the State Action scenario's resultant emissions profile as a modeling constraint, nationwide total reductions were identical. Since both scenarios ultimately only achieve a CO<sub>2</sub>-eq reduction of 45.7% by mid-century, it should be noted neither of these scenarios achieves the United States Paris Agreement ambitions.

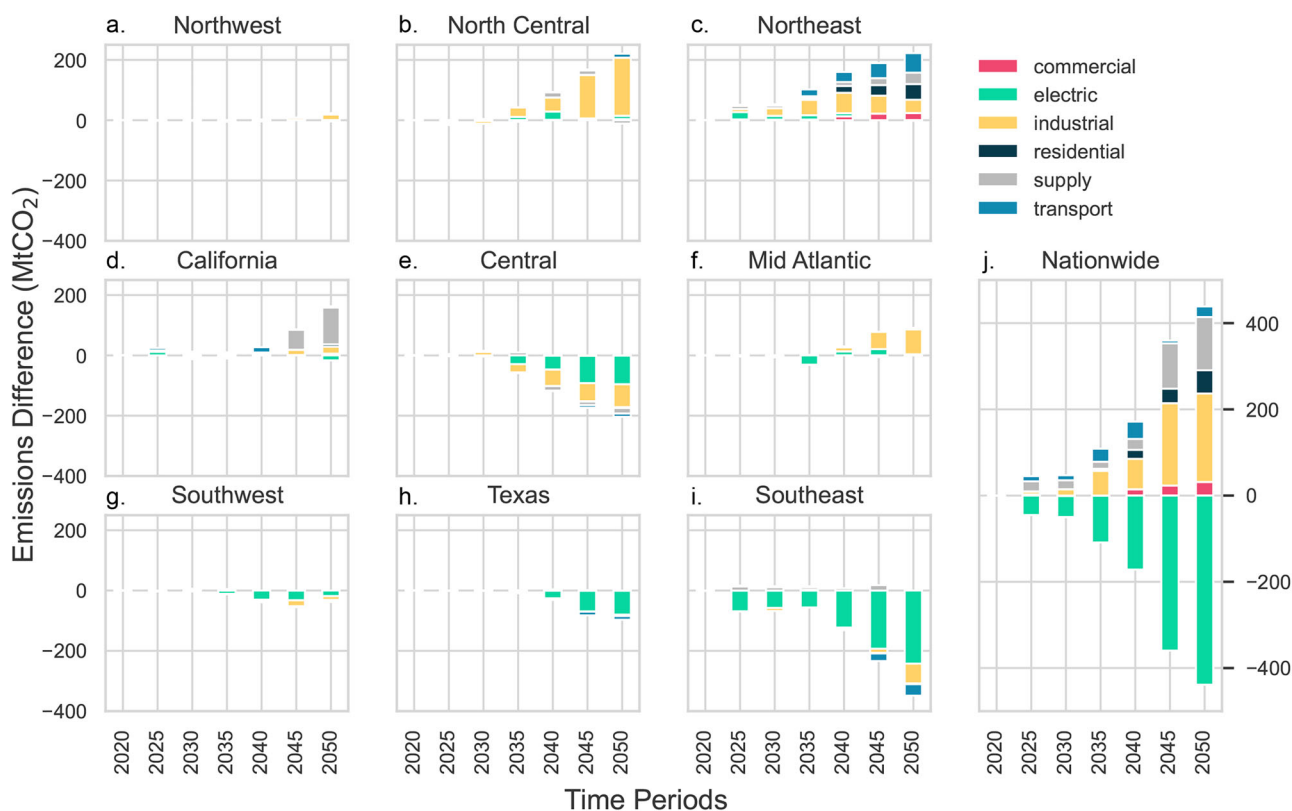


**Fig. 2 | Annual CO<sub>2</sub> emissions by scenario & region, nationwide.** The left bars represent the State Action scenario with 23 states adopting net-zero emission targets, while the right bars achieve comparable overall emissions reductions in the National Action scenario.

Within these results, we present the emissions and technological differences between these decarbonization scenarios. We first report the overall regional emissions variations by sector, followed by a detailed comparison of each scenario's electricity sector. A detailed review of scenario changes in electricity transmission, carbon management practices, and primary energy use follows. Finally, scenario costs are provided for insight into cost-technology tradeoffs.

### State-led decarbonization leads to a surge in electricity emissions and sparks carbon redistribution

Though aggregate national CO<sub>2</sub>-eq emissions are identical between the State and National Action scenarios, as shown in Fig. 2, we see substantial shifts in where emissions occur. Figure 3 shows the emissions differences between scenarios, segmented by sector, with absolute values provided in the Supplementary Information. In Fig. 3, positive values on the y-axis represent higher emissions with the National Action scenario, while negative values represent higher emissions in the State Action scenario. Each sector is comprised of a detailed technological representation in which end use technology selection is endogenous to the model. The transportation sector includes light-, medium-, and heavy-duty vehicle transport, as well as aviation, passenger and freight rail, aviation, marine and off-road applications. Commercial and residential end-use service demands include cooking, heating and space cooling, lighting, refrigeration, water heating, appliance use, ventilation, and other categories. Example demand technologies include room air conditioners, central air conditioners, and heat pumps for cooling demand. Industrial sector end-use demands are segmented into manufacturing and non-manufacturing and include food and beverage, paper mills, petroleum refining, chemical and cement manufacturing, plastics/rubber and iron/steel



**Fig. 3 | Differences in CO<sub>2</sub>-eq emissions by sector.** Positive values indicate higher emissions in the National Action scenario, while negative values indicate higher emissions in the State Action scenario. Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. Under the State Action scenario, the

Southeast, Texas, and Central regions have greater power sector emissions as compared to the National Action scenario. Without the binding constraints from the State Action scenario, the California, North Central, and Northeast regions see higher CO<sub>2</sub> emissions across several sectors.



production, fossil fuels and metals mining, construction and agriculture, with common industrial processes including process heating, conventional boiler use, cogeneration systems, machine drives, facility HVAC, and process cooling.

While both scenarios yield the same CO<sub>2</sub>-eq emissions per time period, including 2547 MtCO<sub>2</sub>-eq in 2050, the regional constraints under State Action leave substantial power sector emissions in the non-participating states, whereas National Action foregoes mitigation in industry and carbon management. Carbon management includes direct air capture (DAC) and at-emission capturing technologies, from which CO<sub>2</sub> may then be stored in geologic reservoirs or converted into fuels. Spatial and sectoral disbursement also varies substantially. Nationwide, we see a sectoral redistribution of CO<sub>2</sub>-eq of 439 MtCO<sub>2</sub>-eq in 2050, 17.2% of total emissions for this time period. This redistribution is entirely reallocated to the electric sector in the State Action scenario. Under the National Action scenario, redistributed CO<sub>2</sub>-eq emissions span all other sectors, with the High and Mixed regions not directly constrained to address their hardest to abate emissions.

To explore these emissions shifts further, Fig. 3 shows a model behavior of targeted regional decarbonization, tracking with the High, Mixed, and Low involvement decarbonization clusters. Low-involvement regions – Southeast, Central, and Texas – have consistently higher emissions in the State Action scenario relative to their National Action scenario outputs. Among these regions, the Southeast has the greatest difference in State Action emissions, with 349 MtCO<sub>2</sub>-eq higher emissions in 2050 as compared to the National Action scenario. This result suggests the Southeast can provide cost-effective mitigation under a national carbon mitigation program due to its cheaper and more readily available resources, namely biomass supply and geologic storage potential for CO<sub>2</sub>-eq. As Table 2 indicates, these regions have carbon reduction commitments in the State Action scenario ranging from 0% (Central & Texas) to 13.1% (Southeast) by mid-century. Mixed-involvement regions, such as the Mid-Atlantic, Northwest, and Southwest, show more modest shifts in regional CO<sub>2</sub>-eq emissions between scenarios. Provided within the Supplementary Fig. 4 and Supplementary Fig. 5 is the percent change in emissions for each region and scenario relative to 2020 levels. The North Central region diverges from the other Mixed-involvement regions, with 200 MtCO<sub>2</sub>-eq additional emissions in its 2050 National Action scenario relative to the State Action scenario, driven primarily by higher emissions in the industrial sector in the National Action scenario. High-involvement regions (i.e., California and the Northeast) fully achieve net-zero by 2050 in the State Action scenario. When alleviating the binding net-zero constraints for these regions, as is done in the National Action scenario, we see a moderate nationwide decarbonization, which accelerates the cost-effective mitigation options of the Southeast and Texas regions. Emissions in California and the Northeast are 146 MtCO<sub>2</sub>-eq and 220 MtCO<sub>2</sub>-eq higher in the National Action scenario's 2050 model time period compared to the State Action scenario, respectively. These higher emissions in California's National Action scenario primarily arise in the supply sector, with a two-fold cause. First, California in the National Action scenario imports additional natural gas for commercial, residential, and industrial applications, increasing California emissions by roughly 58 MtCO<sub>2</sub>-eq for this scenario. Second, California's State Action scenario allocates carbon capture with geologic sequestration to the supply sector, providing an additional 116 MtCO<sub>2</sub> in emissions difference between scenarios.

Low involvement regions select higher emitting technology options when unconstrained in the State Action scenario. Within the State Action scenario, the 439 MtCO<sub>2</sub>-eq additional 2050 emissions from the electric sector (relative to the National Action scenario) come predominantly from the low-involvement cluster regions, with the Southeast, Central, and Texas regions having electric emissions that are 243, 95, and 79 MtCO<sub>2</sub>-eq higher in the State Action scenario

relative to the National Action scenario, respectively. Figure 4 details the changes in electric generation by source between the two scenarios. The State Action plan results in substantially more generation from both renewables and fossil fuel sources, adding 952 TWh in 2050, or a 15% increase in generation as compared to the National Action scenario. Differences in total scenario electricity by region are provided within the Supplementary Fig. 7. This addition of both carbon-intensive and low-carbon generation is driven by the regional heterogeneity in CO<sub>2</sub>-eq constraints, with some regions required to meet ambitious reductions and others left unconstrained. For the low involvement regions – in particular the Southeast – the National Action generation portfolio includes increased solar, wind, battery, and biomass generation; under the State Action plan, without incentive to reduce emissions, more natural gas and coal is deployed in this region.

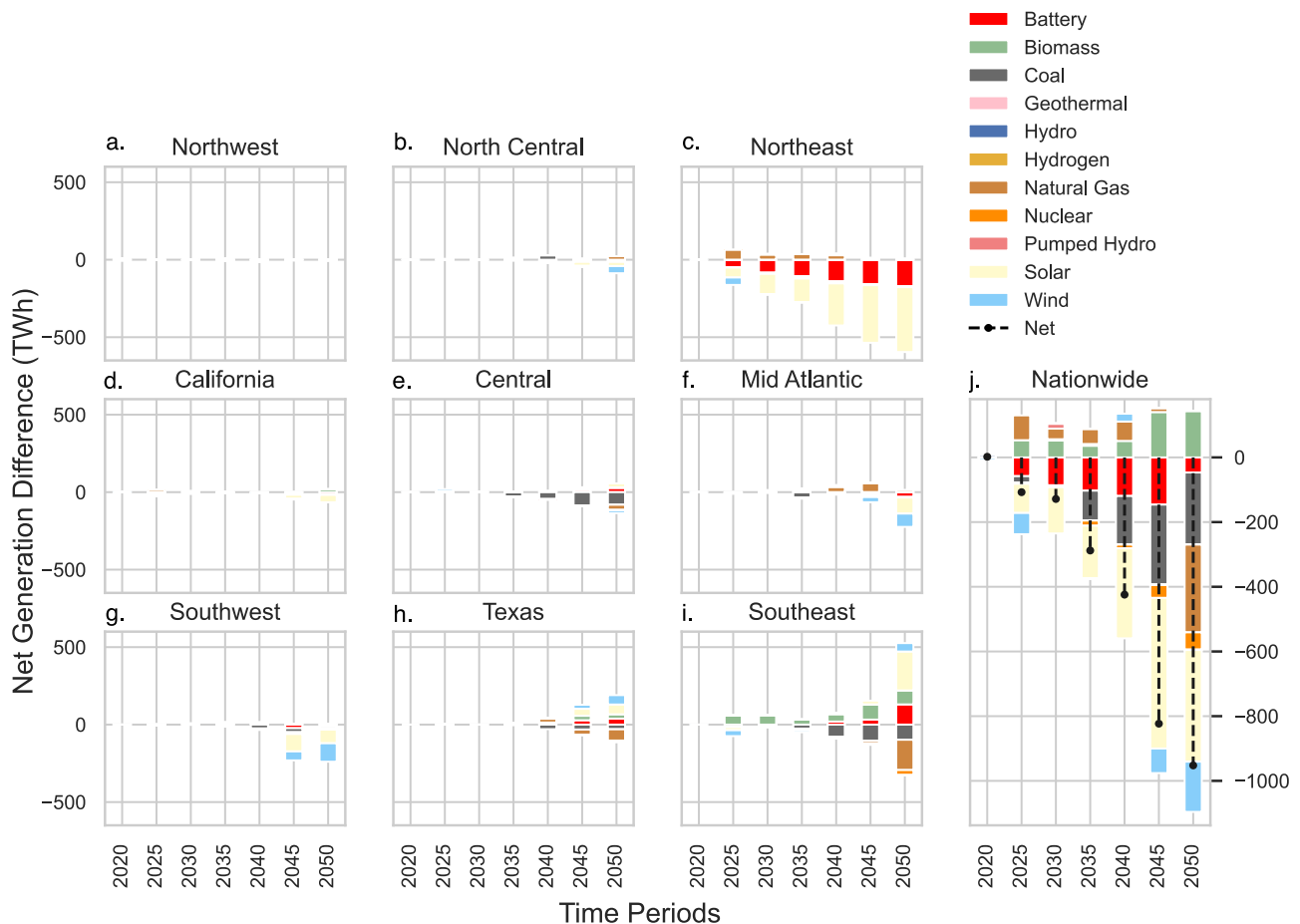
Under the State Action scenario, we see a substantial increase in overall electricity generation. In this scenario, High Involvement regions have to decarbonize all their sectors, which drive the electrification of end-uses. By contrast, the same emissions levels under a National Action scenario can be met with fuel switching in power generation without a drastic increase in end-used electrification. The majority of increased electricity demand in the State Action scenario comes from industrial sector electrification, as shown in the Supplementary Fig. 8.

### Committed regions select distinct decarbonization paths while integrating DAC and renewables

High-commitment regions vary in their approach to achieve deep decarbonization. California and the Northeast, which are constrained to a net-zero mid-century goal in the State Action scenario, meet power sector demands through different modeling choices and use carbon management through direct DAC to different ends. The Northeast invests heavily in solar and storage, using 418 TWh more solar generation and 173 TWh battery throughput in 2050 for the State Action scenario compared to the National Action scenario. The Northeast uses more residential electric heat pumps and increases transport sector electrification in the State Action scenario compared to the National Action scenario, driving this increased demand for electricity. California is projected to add far less new renewable energy, increasing solar generation by 47 TWh in the State Action scenario compared to the levels achieved in the National Action scenario.

To find the cause for this disparity in renewables usage, we first inspect inter-regional transmission. Figure 5 provides the net electricity imports between regions for both the State and National Action scenarios during the 2050 model time period. In 2050, California imported substantially more Southwestern electricity in the State Action scenario compared to the National Action scenario. Net imports between these regions nearly doubles from 252 TWh in the National Action scenario to 461 TWh in the State Action scenario. This increase in imported power from the Southwest occurs in tandem with increased Southwestern solar and wind generation in the State Action scenario. The Southwest adds 88 TWh and 119 TWh of generation from these respective resources in a state-led decarbonization scenario. Provided within Supplementary Figs. 13 and 14 is an hourly representation of California's electricity demand against imported Southwestern electricity and the Southwest's solar and wind generation in the State Action scenario. Comparable results for the National Action scenario are also provided for context. California's own in-region generation is 338 and 385 TWh in 2050 for the National and State Action scenarios, respectively. In a state-led decarbonization, California's most cost-effective model selection is to augment renewable electricity through imports from the Southwest, rather than relying on additional in-house generation.

The mixed-involvement North Central region also experiences an increase in electricity imports in the State Action scenario compared to



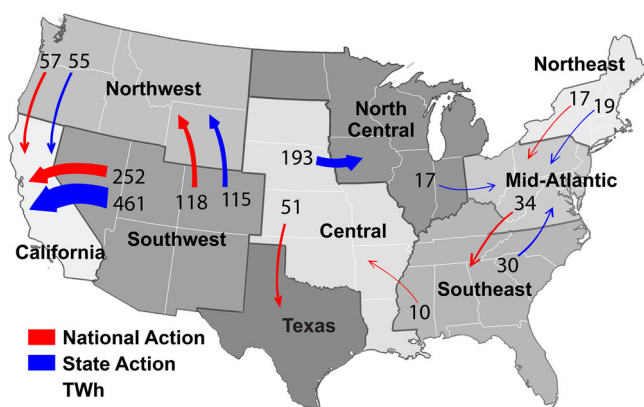
**Fig. 4 | Electricity generation difference. Positive values indicate higher generation in the National Action scenario, while negative values indicate higher generation in the State Action scenario.** Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. State-level net-zero policies drive considerable expansion of electricity generation in the Northeast. Allowing all states to contribute to emissions reductions in the National Action Plan results in additional renewable energy development in the Southeast. TWh = terawatt-hours.

the National Action scenario. In 2050, the North Central region imports 192 TWh from the Central region in the State Action scenario, while contributing minimal exports during the same period. Consequently, the North Central region consumes approximately 20% more electricity than it generates in 2050 in the State Action scenario. While California's net-zero policy spurs solar and wind deployment in the Southwest, the North Central region's imports from the Central region in the State Action scenario increase coal (81 TWh) and natural gas (33 TWh) generation in the latter region, compared to the National Action scenario. It should be noted that this change in inter-regional trade reflects a policy design in which emissions are allocated to the producing, not consuming regions, which enables leakage of emissions. Modeled interregional trade of energy carriers allocates emissions to upstream or processing technologies, meaning that emissions are ultimately attributed to the exporting region rather than importing. In the case of the Central region, its lack of emissions constraint within the State Action scenario means increased coal- and natural gas-based generation exported to the North Central region is permissible, so long as the North Central is not the originating region for this carbon-intensive generation. This same modeling emissions allocation strategy is applied to all regionally traded commodities, including electricity, ethanol, and hydrogen. When considering a heterogeneous decarbonization, such as the State Action scenario, policy design must be cautious to mitigate the risk of emissions leakage. Non-participating regions may increase production of carbon-intensive commodities or electricity, thereby offsetting emission reductions achieved in decarbonizing regions. By magnitude, the North Central's State Action

scenario requires the greatest emissions reduction of any region relative to present-day emissions (579 MtCO<sub>2</sub>-eq). Our analysis shows that the region can meet this target by importing fossil fuels from regions without targets. Thus, one of the most critical decarbonization regions in a state-led scenario may engage in the leakage of coal and natural gas generation from unconstrained regions.

When examining the use of carbon management techniques in high-involvement regions, we see that decarbonization of the power sector alone is insufficient to meet state-led net-zero constraints. Carbon dioxide removal technologies are deployed to meet regional net-zero goals, as shown in Fig. 6. Both California and the Northeast employ direct air capture (DAC) to offset hard-to-abate emissions. In the Northeast, the DAC to fuels pathway is used to offset an additional 78 MtCO<sub>2</sub>-eq in 2050 compared to the National Action scenario, ultimately being used for synthetic fuels in the transport sector (Fig. 7). This removal amount represents 35% of the emissions difference between the State (0 MtCO<sub>2</sub>-eq) and National Action (221 MtCO<sub>2</sub>-eq) final 2050 emissions. In California, DAC with geologic storage offsets an additional 116 MtCO<sub>2</sub>-eq compared to the National Action scenario, and DAC to fuels accounts for 15 MtCO<sub>2</sub>-eq in the State Action scenario's 2050 model time period. Combined, these DAC technologies account for 90% of the emissions difference (146 MtCO<sub>2</sub>-eq) between California's scenarios in 2050. Both high-involvement regions take advantage of DAC, but to different ends. In part, this difference in end use arises from assumptions regarding geologic sequestration potentials. While California has a modeled 29.8 GtCO<sub>2</sub>-eq storage potential, the Northeast is permitted only 0.4 GtCO<sub>2</sub>-eq<sup>29</sup>.

For the transportation sector, we see increased use of electricity and novel fuels in regions which require deeper decarbonization. Figure 7 shows that, when many regions engage in emissions reduction, they rely on the transport sector for some amount of that reduction. Mitigation in the transportation sector tends to vary more significantly over intervening time periods, partly because the shorter lifetimes of transportation technologies allow for more frequent shifts

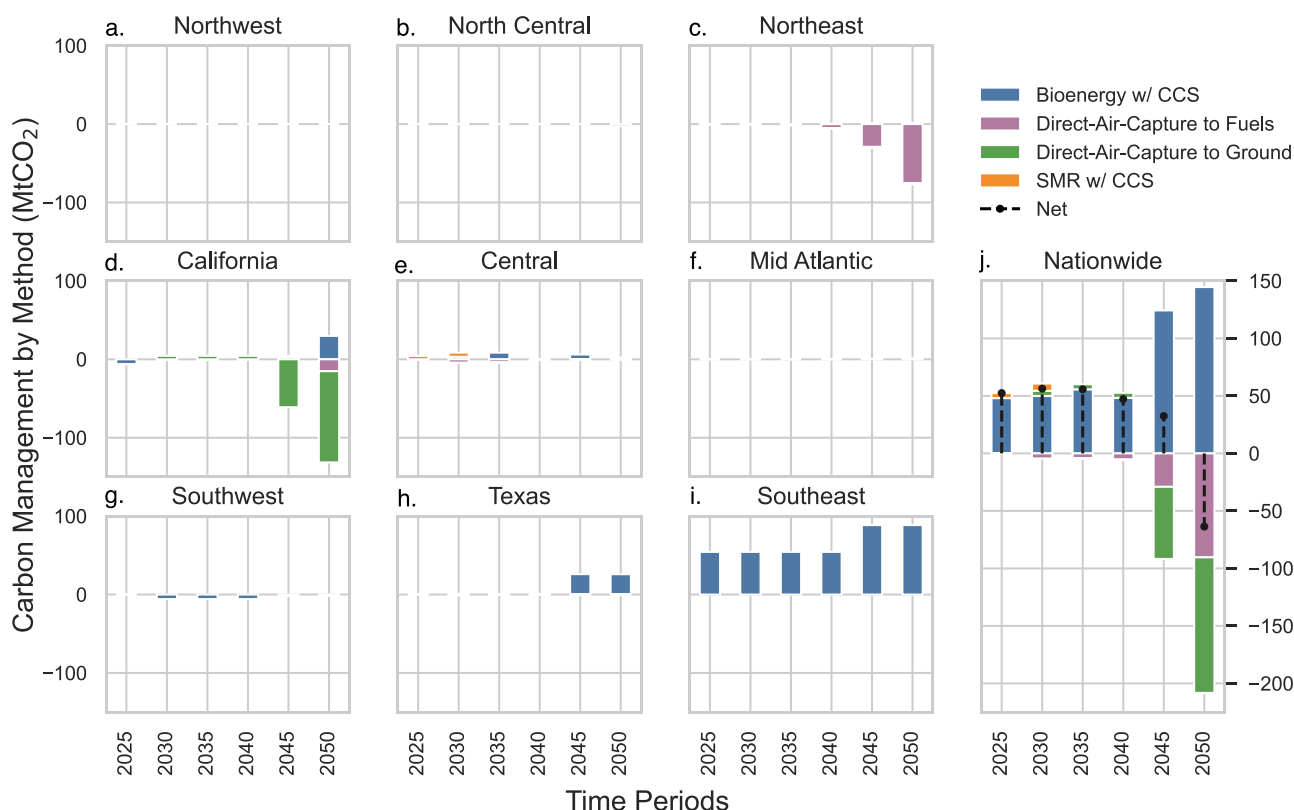


**Fig. 5 | Net electricity imports in region 2050.** Red arrows show the net flow for the National Action scenario, while blue arrows show flows for the State Action scenario. The net-zero goals in the State Action scenario result in greater electricity imports from the Southwest to California, Central to North Central, and the Southeast to Mid-Atlantic. TWh = terawatt-hours. State map obtained via Creative Commons license<sup>44</sup> and modified using Adobe Photoshop.

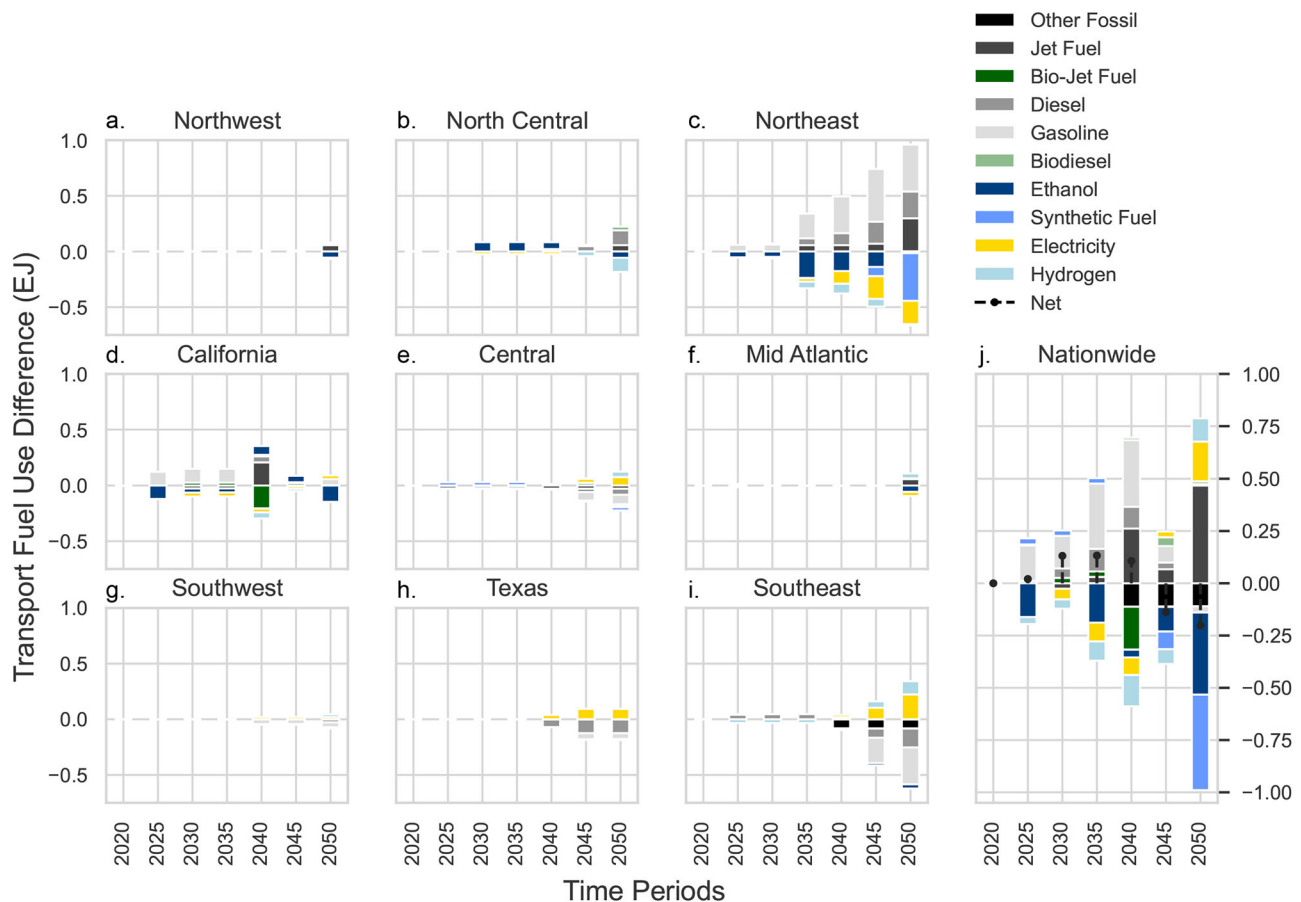
in technologies or fuels compared to sectors like power generation. High-involvement regions within the state-led scenario select lower-emission fuels than the federally-led scenario. The California and Northeast's National Action scenario included more jet fuel, gasoline, diesel, and other fossil fuels relative to their State Action scenario outputs. When switching to the State Action scenario, the Northeast instead selects synthetic fuel from DAC, electricity, ethanol, and hydrogen, while California trades jet fuel for bio-jet fuel. The low-involvement regions display behavior aligned with business as usual in the State Action scenario, deploying more gasoline and diesel. When able to contribute to decarbonization efforts, as in the National Action scenario, they swap these fuels for electricity and hydrogen. Ethanol is an additional fuel used more often in the State Action scenario than the National Action scenario in the Northeast region and, to a lesser extent, the North Central and Mid-Atlantic regions. These regions do not increase their biomass primary fuel use, but rather import corn ethanol from the Central region. Given that our modeling framework attributes emissions at the point of generation, this trade de facto permits emissions leakage in cases where the exporting region is constraint-free related to the produced fuel. In this case, ethanol production (and its associated emissions) is permissible in the Central region for the North Central and Mid-Atlantic regions' use, since the Central region lacks a State Action scenario emission constraint. Nationwide, the primary energy consumption differences between scenarios is provided in the SI, showing the extensive addition of biomass in the State Action scenario's Central region.

### Uninvolved regions adhere to expectations, but emerge as crucial for federal decarbonization

When allowing the emissions reductions to be achieved anywhere in the country, we see that Southeastern bioenergy with carbon capture



**Fig. 6 | Carbon management by method.** Positive values indicate increased carbon management in the National Action scenario, while negative values indicate increased carbon management in the State Action scenario. Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast, and (j) Nationwide results. CCS = Carbon capture & storage, SMR = Steam methane reformation. The National Action scenario results in bioenergy with CCS, predominately in the Southeast, while the State Action scenario results in direct air capture in California and the Northeast.



**Fig. 7 | Transportation sector fuel use difference.** Positive values indicate higher fuel use in the National Action scenario, while negative values indicate higher fuel use in the State Action scenario. Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast, and (j) Nationwide results. Transportation fuels vary greatly between the

two scenarios in the Northeast, with the State Action scenario driving electrification, synthetic fuel, and biofuel use, and the National Action scenario using more fossil fuels for transportation. The opposite trends are shown in the Southeast. EJ = exajoule.

& storage (BECCS) proves to be a cost-effective alternative to direct air capture. As shown in Fig. 6, the Southeast deploys considerable amounts of BECCS in the National Action scenario. Further striking is this rapid additional deployment in the early model time periods, adding more than its National Action counterpart as early as 2025. Perhaps of more interest than BECCS deployment in isolation, though, is the context in which this deployment occurs. The Southeast's emissions reduction from 2020 – 2050 in the State Action scenario was 80 MtCO<sub>2</sub>-eq, equivalent to a 9.9% decrease. National Action scenario reductions were far greater at 429 MtCO<sub>2</sub>-eq for the same timeframe, equivalent to a 53.3% decrease in the region's emissions. Within a federally-led decarbonization effort, the Southeast provided the greatest overall reduction in emissions across all regions. These reductions achieved by the Southeast in the National Action scenario also exceed the absolute emissions reductions of both high-involvement regions, California and the Northeast, in the State Action scenario (394 and 345 MtCO<sub>2</sub>-eq). It is only the North Central and Mid-Atlantic regions, the two regions with the greatest initial emissions, which reduce emissions to a greater extent, though doing so in the State Action scenario rather than the National Action.

Beyond BECCS, we see that the Southeast also decarbonized its electricity generation under the National Action scenario (Fig. 4), offering cost-effective mitigation in meeting the national decarbonization target. The substantial emissions reduction of the Southeast in the National Action scenario also adds context to the previously discussed increase in coal and natural gas generation in the

State Action scenario. Not only do fuel shifts occur, but the National Action scenario employs by 2050 an additional 199 TWh of electricity generation for transportation electrification compared to the State Action Plan. Like the high-involvement regions in the State Action scenario, the Southeast within the National Action scenario employs a two-fold method for decarbonization: a marked increase in electricity generation, shifting end uses from carbon-intensive to zero-emissions, and the implementation of carbon management at a substantial scale. The Southeast may then be considered the key decarbonizing region of the National Action scenario. Biomass, wind, and solar energy within this region is cost-preferred from a nationwide perspective, but remains unused when neither itself nor neighboring regions have a deep-decarbonization requirement.

#### Cost vary little despite technology deployment distinctions

While the State and National Action scenarios result in substantially different technology deployments and substantial regional fuel shifting, system cost differences are low. The system-level discounted fixed, investment, and variable costs are provided in Supplementary Fig. 17 and Supplementary Table 3, revealing only a \$280B difference in discounted costs over the entire model lifetime, with differences in investment costs accounting for the majority of this. With a total scenario cost of \$40.20 T for the State Action scenario and \$39.92 T for the National Action scenario, relying on state-level decarbonization policies increases energy system costs by 0.7% relative to a nationwide least-cost pathway.



While the overall cost differences are minor, we observe more substantial regional differences, also shown in Supplementary Table 4. The Northeast and Central regions stand out, contributing net increases of \$167 billion and \$117 billion in the State Action Scenario, respectively. The additional State Action scenario costs in the Central region are likely caused by additional exports of electricity to the North Central region, as Temoa allocates associated costs to the exporting region. The Northeast and Central regions have 4.3% and 3.3% higher costs in the State Action scenario compared to the National Action scenario. Cost shifting between scenarios reveals that regions without emissions constraints or with lower emissions constraints than their counterparts experience heightened variable costs. Conversely, scenarios imposing greater emissions reduction requirements on specific regions typically result in increased fixed and investment costs. For instance, in the Northeast, under the National Action scenario, additional natural gas consumption drives increased variable costs. In contrast, the State Action scenario opts for solar, which incurs no variable costs. The opposite trend for variable costs occurs for low-involvement regions between scenarios.

## Discussion

The future of federal energy and climate policy is marked by high uncertainty, and contested federalism is poised to take center stage in the upcoming decades' climate debate, regardless of whether states and the federal government choose to collide, compete, or collaborate<sup>20</sup>. Advocacy groups have recently called for a multi-tiered government collaboration, aptly named "New Climate Federalism," which recognizes the strengths of each government level<sup>30</sup>. However, the return of the Trump Administration will greatly reduce the likelihood of passing climate-friendly energy policy at the national level. We have two major political parties with vastly different climate objectives. One party advocates for existing renewable energy tax incentives, forthcoming vehicle emissions mandates from the Environmental Protection Agency, and the United States' participation in the Paris Agreement, while the other explicitly seeks their removal. For this reason, a piecemeal approach to decarbonization using the strengths of the states may offer the most resilient and plausible pathway for further reductions in emissions. This study seeks to answer what that decarbonization endeavor may look like and generate key insights for policymaking in doing so.

First and foremost, our results support existing literature surrounding the need for electrification during a deep decarbonization of the United States. Decarbonizing the power sector in climate-ambitious regions is a key action in our state-led scenario, along with increasing generation to meet electrified end-use demands such as the transport sector and residential heating. However, this pathway does not come without tradeoffs. Low-involvement regions in a cooperative-federalist energy transition have less incentive to decarbonize power generation, continuing the use of natural gas and coal. Ultimately, our state-led results show a power sector that is more carbon-intensive than its federally led counterpart. In 2050, the state-led scenario's power sector carbon intensity is 46 gCO<sub>2</sub>-eq kWh<sup>-1</sup>, while a federally-driven scenario's power sector has eight times less at 5.7 gCO<sub>2</sub>-eq kWh<sup>-1</sup>. Both of these results, however, indicate the power sector will have a lower carbon intensity than the current 2022 U.S. estimate of 376 gCO<sub>2</sub> kWh<sup>-1</sup><sup>131</sup>.

Furthermore, low-involvement regions may contribute to potential emissions leakage, as shown by the Central region's exporting of coal for electricity generation and corn-based ethanol for transportation to those with deep-decarbonization requirements. By accounting for emissions in the regions in which they are generated, our approach allows for such emissions leakage. In comparison to a previously modeled Temoa business as usual scenario, which incorporates modeled IRA provisions but lacks emissions constraints, our State Action scenario demonstrates emissions in the Central region that are

approximately 15 to 29% higher between 2035 and 2050. Provided within Supplementary Information is a comparison of the Central region's state-led scenario emissions with the reference case. This comparison indicates that the region's behavior within the State Action scenario is not neutral, but indeed increasing emissions to meet energy demands in deeper-decarbonizing regions. Temoa's emissions accounting method may be, however, an accurate representation of outcomes associated with state- or region-level efforts to reduce emissions, as demonstrated in other studies<sup>32</sup>. Beyond this, international transmission projects such as the New England Clean Energy Connect (NECEC), connecting Canadian hydropower to the New England region, further alters the dynamic of inter-regional energy accounting. This accounting approach requires further inquiry and suggests the need for careful policy design to avoid adverse outcomes like emissions leakage. Expanding transmission capacity to export carbon-intensive electricity to another region may avoid more costly in-region mitigation options, but undermines the stated policy goal of emissions reduction. Beyond electricity, policymakers must also consider other traded commodities, such as ethanol and hydrogen, for which inter-regional transfer can be largely unconstrained. Policy mechanisms to address this adverse effect include border adjustments for imported energy carriers, using life cycle assessment methods to determine emissions, and broadening the group of states and regions participating in the climate mitigation policy. From a modeling perspective, future work should consider reformulated accounting approaches that reflect these considerations.

For regions with deep-decarbonization constraints in the state-led scenario, we find they will be unable to employ a one-size-fits-all strategy for net-zero goals. The Northeast adds extensive solar and battery resources to decarbonize its power sector and provide zero-emission generation for residential electric heat pumps. California takes a different approach, instead importing Southwestern solar and wind. For both regions, however, direct air capture technologies are used. Like the implementation of renewables, their scales and end-use differed. Broadly, the outcomes of these two regions in the state-led scenario demonstrate the need for an energy policy designed to play to both a region's strengths and needs.

This notion of playing to the comparative advantages of United States regions is perhaps best displayed within Texas and the Southeast in the National Action scenarios, where a moderate national emission constraint is sufficient to motivate added BECCS, along with solar and wind generation. The substantial addition of these technologies under federally-led decarbonization changes the involvement of these regions entirely, turning politically reluctant regions into significant contributors to climate mitigation. The Southeast and Texas were responsible for 27% of the National Action scenario's cumulative emissions reduction, compared to a combined 6% in the State Action scenario. Significantly, this switch in decarbonization contribution requires few added costs – an annualized \$1.7 billion and \$65 million for the Southeast and Texas, respectively – representing 0.04% and 0.02% of their 2022 Gross Domestic Product<sup>33</sup>. Though, it must be mentioned that in the application of technologies such as BECCS in the Southeast, this additional deployment begins as early as 2025. Such a rapid added deployment of technology may have real-world constraints, but its model cost-effectiveness remains. It should be noted that these costs may not even be truly borne by them, as costs are assigned to producing regions, but additional revenues would also likely follow.

The contribution from the Southeast and Texas in our federally-led scenario supports evidence that states expressing lesser interest in pursuing decarbonization initiatives will be vital for nationwide net-zero efforts<sup>34,35</sup>. Studies examining the U.S. energy system in a mid-century deep decarbonization have already shown that the Southeast will need to increase its utilization of biomass resources. One study estimates that raw biomass feedstock production may need to

increase as much as seven-fold. This region would consequently see a growth in biomass shares from 8% of U.S. production in 2020 to 20% in 2050<sup>35</sup>. Given both scenarios had CO<sub>2</sub> emissions reductions of 46%, falling considerably short of broader national objectives, determining means of stimulating carbon-reduction efforts in these low-involvement regions could serve as a meaningful extension of this paper's scope.

The extreme technological sensitivity of the United States' energy system to shifting administrative authority shows the interdependence of our energy system beyond political boundaries, and a current disconnect between who wants to decarbonize and where it is most cost-effective. Our federalist decarbonization shows politically motivated regions seeking to reduce emissions, but must employ costly deep-decarbonization technologies to meet net-zero goals. The Northeast spends an additional \$117 billion within the State Action scenario, and the Central region spends an additional \$117 billion while meeting the North Central's needs. These costs are offset at the national level through the use of less expensive fossil-fuel resources elsewhere. The collective-effort counterpart instead taps into the abundant low-carbon resources of our politically disengaged regions, more directly Texas and the Southeast, to avoid the more costly technologies. Transitioning between these administrative scenarios appears to have little cumulative system cost consequence.

Collectively, these results convey that we may be able to reach the same emissions ends through vastly different means, at similar costs. This turns on its head the notion that a state-driven energy transition is inherently inefficient, slow, and more costly. Instead, it suggests a decarbonization pathway where expenses might be borne by the politically willing. Given the tendency for climate and energy policy support to fall closely along partisan lines, this presents a far more politically resilient decarbonization strategy than alternatives relying solely on comprehensive federal policy.

However, it is important to note that neither scenario achieves nationwide net-zero emissions by 2050, which is necessary to meet the global climate stabilization target set by the Paris Agreement<sup>4</sup>. Ultimately, low-involvement regions will have to engage in emissions mitigation efforts to reach national net-zero emissions in the energy system by 2050. Additionally, pursuing a national net-zero pathway may result in different emissions trajectories in high-involvement regions, such as California and the Northeast, compared to those presented in this paper. For example, a national net-zero emissions pathway could allow for residual emissions in the Northeast while less costly carbon dioxide removal is deployed in regions with high CO<sub>2</sub> sequestration potential (like Texas and the Central region). These differences could reveal economic inefficiencies arising from a federalist energy transition approach when pursuing decarbonization options to achieve net-zero emissions. Therefore, future research should evaluate these divergent emissions trajectories, including analyzing technology and fuel deployments and their cost implications.

That said, the National Action scenario is still useful as a guide to where future federal intervention might be best placed and where targeted industrial policy may prove most effective. Because the State and National Action scenarios feature significantly different key players in their decarbonization strategies, and the state-led scenario better reflects current political dynamics, federal policymakers can strategically leverage low-involvement regions' decarbonization potential through targeted policies. For instance, Texas and the Southeast's wind, solar, and biomass resources are invaluable in achieving deeper decarbonization objectives, yet these resources are shown as untapped without additional policy intervention. Targeted federal policies, aimed specifically at encouraging these resources in these places—roughly akin to the Department of Energy's recent establishment of Regional Clean Hydrogen Hubs or the Department of Agriculture's past establishment of the Biomass Crop Assistance

Program (BCAP) Project Areas— might be sufficient to encourage participation of otherwise-sidelined resources. At a cost differential of just 0.04% and 0.02% of Southeast and Texas Gross Domestic Product, the aggregate costs to unlock a fivefold increase in emissions reductions need not be extreme. Past examination of legislative support affirms that such economic incentives also tend to have the greatest bipartisan support as compared to mandates and standards<sup>36</sup>.

While further U.S. decarbonization will likely be driven by state ambition—particularly in the near-term given the outcome of the 2024 presidential election—our results indicate that technology choices of this pathway will be substantially different than a collective decarbonization. However, system costs nationwide will be near-identical to its homogeneous alternative, shifting costs to those politically willing. Leakage concerns emerge as politically disengaged regions are confronted with systemic changes triggered by those seeking deep decarbonization, prompting adjustments to their own energy systems. This stylized subnational action also fails to meet larger stated federal ambitions. Furthermore, even this reduced mitigation level will be challenging to successfully execute. As a result, we suggest this paper's National Action scenario be a means to identify where future federal intervention may be most cost-effective and politically resilient. Both scenarios achieved a 45.7% CO<sub>2</sub>-eq reduction by 2050 relative to 2020 levels, short of Paris Climate Agreement ambitions. As such, creating incentives to reduce emissions in politically disinterested regions will bring a state-led decarbonization closer to declared national emissions targets. The disconnect between the leading regions of our state-led and nationally-led scenarios points towards a discrepancy that can further inform action by federal policymakers. Modeled cost differences between scenarios of these low-involvement regions implies even small investments can instantiate a technological tipping point from carbon-based capacity towards renewable and negative-emissions technologies.

## Methods

To explore the impact of heterogeneous policy development on technology deployment for decarbonization, we employ a two-scenario model design. The State Action scenario is informed by real-world political indicators as signals of greater state climate policy ambition by mid-century. The second scenario, National Action, is informed only by resultant nationwide CO<sub>2</sub>-eq State Action scenario emissions reductions, set as a nationwide constraint. In this section, we introduce the ESOM for modeling our scenarios and then provide a detailed description of the methods employed for the State Action and National Action policy scenarios.

### Temoa model design

To assess the State and National Action policy scenarios, we use the Tools for Energy Model Optimization and Analysis (Temoa), a detailed open-source ESOM. The benefits of this model's use are three-fold. It is fully open-source, has an economy-wide representation of the U.S. energy system, and permits endogenous model selection of end-use technologies. Designed as a process-based network in which technologies are linked via energy commodity flows, processes are exogenously given a set of techno-economic parameters, including investment costs, operations & maintenance (O&M) costs, conversion efficiencies, emission rates, and availability factors. The core structure of this model is a linear problem optimizing for least cost, with the model time horizon covering 2020 through 2050 in five-year increments. Within each 5-year time period, each year is assumed to be identical. Operational requirements and sub-annual electricity supply and demand balancing are addressed through a representative days approach. Each year's operations are modeled over eight days at an hourly resolution, with representative days selected from datasets including energy demands and varying renewable energy capacity factors. This method has been used to balance computational

requirements with operational detail. Results are solved myopically rather than with perfect foresight, with nine US regions: California, Central, Mid-Atlantic, North Central, Northeast, Northwest, Southeast, Southwest, Texas. Model regions are chosen for their similarity in aggregation to U.S. electric balancing authorities while following state boundaries.

The formulation of the Temoa database inputs, assumptions, and core constraints follows closely with many previous studies. Temoa's algebraic formulation and initial design is presented in Hunter et al.<sup>37</sup>, while the database inputs for this study align with the recent publication by Sinha et al.<sup>6</sup>. Core constraints within Temoa which define the energy system network and drive endogenous technology selection include the demand constraint, timeslice-variable commodity balance constraint, and an annual commodity balance constraint. The demand constraint ensures supply meets specified end-use demands across all time periods and timeslices of the representative days. The timeslice-variable commodity balance constraint ensures commodities with use varying across timeslices is balanced, while the annual commodity balance does the same for commodities produced at a constant annual rate. Additional constraints applied within the model include a capacity constraint to ensure activity can be achieved, with optimized decision variables including installed capacity, associated activity, fuel shares, supply, and end-use technology. Finally, physical and operational constraints, including ramp-up/down considerations, energy storage discharge rates, and reserve margin requirements, are modeled as well. Model source code for Temoa is available on a GitHub Repository<sup>38</sup>. Previous studies that relied on Temoa include those by DeCarolis et al., de Queiroz et al., Patankar et al., and Bennett et al. refs. 39–42.

Our approach identifies least cost options to meet exogenous end use service demands, such as vehicle miles traveled by vehicle class. The decisions available within the model include shifting technologies with improved efficiency or lower emissions to meet the end use service demands. Mitigation measures that reduce the levels of service provided (e.g., telecommuting that reduces vehicle miles travelled) are not explicitly considered in our analysis, but these measures are unlikely to provide significant mitigation potential compared to supply-side or efficiency improvements.

The scope of our analysis broadly covers emissions from the energy sector including fossil fuel combustion in agricultural processes, but does not include emissions from some agricultural activities such as soil management, enteric fermentation from livestock, and manure management, which were responsible for 9.4 percent of the gross U.S. greenhouse gas emissions in 2022<sup>43</sup>. Expansion of the scope to include these emissions would provide additional mitigation opportunities and challenges in achieving net-zero emissions.

### Input databases & modeled constraints

For this analysis, input data included projected end-use service demands reflecting regional and temporal trends, commodity and technology costs, supply curves, and anticipated technology efficiencies. Provided in the Supplementary Information section is a table-based breakdown of input data source and content. In this study, we include up-to-date IRA provisions.

### Data availability

The datasets generated during and/or analyzed during the current study are available at <https://github.com/TemoaProject/oeo/tree/v3.0.0-dev>. Source data for Figs. 1, 2, 3, 4, 6, 7, and Supplementary Figures are provided as a Source Data file. Source data are provided in this paper.

### Code availability

The code describing the open-source energy system used in this study is available in a public GitHub repository: <https://github.com/TemoaProject/temoa>.

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## Author contributions

G.M. performed the analysis and led the writing the paper; C.G. analyzed policy and contributed to writing; A.V., K.J., and A.S. performed analysis and collected data; P.J. and J.J. conceived and designed the analysis; supervised the analysis; edited the paper.

## Competing interests

The author declares no competing interests.

## Additional information

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**Correspondence** and requests for materials should be addressed to Jeremiah X. Johnson.

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