ABSTRACT

MOUAT, GAVIN MICHAEL. Divergent Technological Pathways Under State and Federal Decarbonization Policies (Under the Direction of Dr. Jeremiah Johnson and committee members Dr. Christopher Galik and Dr. Emily Berglund).

Despite the potential cost-effectiveness of comprehensive federal policy for greenhouse gas mitigation, political challenges constrain its enactment. In the absence of, or in addition to, further federal action in the United States, climate-minded states may enact ambitious mitigation strategies, including net-zero targets. Using a detailed energy system optimization model (ESOM) for the US, we explore the consequences of 23 clean energy policy-oriented states pursuing a net-zero strategy and compare the resultant technology deployments to a federal carbon cap scenario achieving the same CO_2 emissions mitigation. We find that state-led decarbonization yields notably different technology sets relative to a federal policy of comparable CO_2 mitigation, with a small increase (0.7%) in discounted system costs until 2050. The state-led decarbonization pathway relies more heavily on electrification than the federal scenario, with 952 TWh more generation in 2050 and a 17.2% reallocation of emissions to the power sector. We find increases in solar, wind, and battery storage in climate-minded regions, while coal and natural gas-fired generation increases elsewhere. Direct air capture was a critical tool for emissions reduction in all regions with a state-led, net-zero mid-century goal. California sequestered an additional 131 $MtCO_2$ in 2050 via direct air capture (DAC) in the state-led scenario, constituting 90% of the additional 2050 emissions reduction necessary to meet net-zero ambitions. The Northeast region also used DAC in the state-led scenario for 77 $MtCO_2$ removal (35% of its additional emissions reduction requirements) for synthetic transport fuels rather than sequestration. In the federally-led decarbonization scenario, the Southeast cost-effectively contributes to decarbonization through the use of bioenergy with carbon capture and storage and

increased renewables generation. The differences in technology deployment between these scenarios demonstrates the potential for dramatically different U.S. energy portfolio futures that reach comparable levels of greenhouse gas mitigation.

Divergent Technological Pathways Under State and Federal Decarbonization Policies

by
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BIOGRAPHY

Gavin Mouat was born in Newport Beach, California to parents Baxter and Rob Mouat. Spending his formative years first in California and then Colorado, much of his early life was spent camping in the Rocky Mountains with his mother and enjoying the beauty of the Front Range. In 2008, his family moved to North Carolina, where he attended South Iredell High School in Statesville, NC, graduating in 2018. Throughout his time in secondary school, Gavin displayed a passion for the sciences equally met by a love for the earth and its natural systems, an appreciation of emotional expression, and beyond all a wish to leave the world a better place than he found it. This ethos made him enthralled with the intersection of engineering and the social sciences, particularly public policy, and ultimately led to his joining the Department of Civil, Construction & Environmental Engineering at North Carolina State University for his undergraduate degree. While an undergraduate in Environmental Engineering, Gavin worked in a variety of settings. He first was an undergraduate researcher with Dr. Detlef Knappe for the GenX Exposure Study, where he helped quantify PFAS concentrations in water samples from Wilmington and Fayetteville, NC. His following summers included work as a construction engineering co-op and hydraulic engineering intern. Despite this vast array of undergraduate experiences, Gavin found himself wanting to be closer to the heart and soul of the energy transition, both in the U.S. and abroad. While taking the courses “Renewable Energy & The Grid” and “Energy & Climate,” he spoke with Dr. Joe DeCarolis about making a change in his career focus from traditional environmental engineering to energy systems, and Dr. DeCarolis helped him make this shift. Graduating in May of 2022 with a Bachelor of Science in Environmental Engineering, he immediately began work on his Master of Science in Environmental Engineering at NC State, this time around with a concentration in Energy

Systems Analysis and under the advising of Dr. Jeremiah Johnson. Joining the Open Energy Outlook research group in the summer of 2022, Gavin dedicated his time as a graduate student to both energy systems engineering and public policy, earning a Graduate Certificate in Policy Analysis during his graduate tenure in addition to his master's degree. While with the Open Energy Outlook, Gavin was lead author for the to-be published paper "Divergent Technological Pathways Under State and Federal Decarbonization Policies," the work of this very thesis. Following graduation, he intends to find work which brings sound engineering judgement to the energy transition conversation.

ACKNOWLEDGMENTS

It's hard to get out all of the acknowledgements I'd like in a few pages, but I'd like to start where my graduate degree began. As a senior in undergraduate, I remember sitting in Dr. Joe DeCarolis' "Energy & Climate" course and finding myself in love with his work. Coming at a time in my life where I felt uncertain about the path laid ahead, I remember emailing Dr. DeCarolis asking to sit down during office hours and get his advice on how to pivot into the "energy world." He immediately agreed, listened to my thoughts, and gave his two cents on where I could find work that I was passionate about. Without his early help, I nearly certainly wouldn't have chosen to obtain a graduate degree, and for that I'm incredibly thankful to him.

Though Joe helped kick things off for me in this education and ultimately my career, it was the help and advising of Dr. Jeremiah Johnson which allowed my ambitions to flourish. I remember telling him how vehemently invested I was in blending energy systems engineering with public policy research, and it was his willingness to humor me which led to such a fulfilling last two years. This paper nearly fell in my lap, and it felt somewhat poetic that the idea for the work within the OEO team popped up when I first was joining. Beyond helping me find fulfilling research, though, Jeremiah has shown me what it means to be an excellent educator, professional in your field and compassionate mentor. He taught me to push my intellectual limits when I felt out of my depth and gave me confidence when in doubt. Beyond anything, though, he always made me feel like I was working with someone who cared not only about the work we did, but that I was gaining something from it, too. I'm grateful for his mentorship these past few years. Working with him has not only made me a better researcher, but a better person.

The members of my committee must not go without thanks, and because of that I'd like to give gratitude to both Dr. Christopher Galik and Dr. Emily Berglund, both of whom had immense impact on my time as a graduate student. Chris, as I'd told him during my thesis defense, was the professor who gave me the time of day in the policy world. While a joke in some regards, it was his sincere desire to help me integrate public policy research into my studies which made it happen. His course "The Public Policy Process" taught me how to interpret policy through a variety of frameworks, and his aid has allowed me to now (cautiously) self-title myself an "interdisciplinary researcher." Dr. Berglund's course "Complex Adaptive Systems" was perhaps the most challenging I took as a graduate student. It's likely that was the case because of the high standard she sets for her students, but that's also what made it so valuable. Her advice taught me how to approach wicked problems through systems thinking, and her literature review assignments and consequent presentations left me a far better communicator than I entered the class. She's an excellent testament to the quality of the CCEE Department's Professors.

If there was one person to thank for helping me through a few tough times the last two years, it would have to be Dr. Aditya Sinha. He is perhaps one of the kindest and most driven people I've ever met, and working alongside him made me once again the researcher I am today. His tenacity and problem-solving with Temoa taught me to never stop trying and inspired me to learn the data analysis skills I have today. At the end of it all, he was also someone I knew I could trust and seek advice from. Adi, truly, thank you.

As an avid runner, it would be ridiculous if I left out that part of my life in this, so I'd like to extend a hearty thanks to everyone who has been a part of my experience on the NC State Club Cross Country and Track Team. This was the first group of people I met when entering undergraduate, and some of those teammates have remained my closest friends ever since. Through our shared love for running, I found people dedicated to always finding a better version of themselves. As I write this, I can't help but think of Matthew Staehle, Danny Sodano, Spencer Husen and Andrew Whitesell. They have all remained close friends since, and for good reason.

Since I'll be joining the energy space in the future, I would be remiss if I didn't say thanks to everyone who has since encouraged me to work in this field. To Autumn Proudlove, Brian Lips and everyone else on the North Carolina Clean Energy Technology Center's Policy Team, thank you for being the first folks ever to trust me to work in energy policy. To Steve Kalland, the Center's Director, thanks for humoring me in the Student Energy Club's endeavors and in helping me grow as a professional.

To my loving girlfriend, Anna Luking, thank you for putting up with my stress over these last few years, and for being so compassionate and understanding. You're a remarkable example of empathy and kindness in my life, and it's made me a better person.

Finally, I would like to thank my family for their love and support over the past two years. My sister, Maggie Mouat, has always been the person who allows me to be my fullest self. Never judgmental but always honest, she's been a person whom I've always been able to go to when times are rough, and who I care for as one of my best friends. My Aunt and Uncle, Nancy Mouat and Nick Chiulos, have been some of my biggest supporters, never telling me to settle for anything less than my dream and providing any help they can to get me there. Nick has been a source of professional and personal advice in my life that has changed who I am, and I'm grateful. Last, but certainly not least, I'd like to acknowledge my mom, Baxter Mouat. Out of state but always thinking about me, I've always known you were a phone call away and enthusiastic to hear about how my life's going. Though you were just saying what you thought, telling me I "somehow always figure it out" led me to believe that true, and I hold that belief near to my heart. You're my greatest support.

TABLE OF CONTENTS

LIST OF TABLES xii

LIST OF FIGURES xiii

Chapter 1: Introduction 1

1.1 The Rise of Bottom-up Decarbonization Strategy 1

1.2 Energy Systems Optimization Modeling of Decarbonization Pathways 4

Chapter 2: Results 7

2.1 Policy Scenario Design 7

2.2 Scenario Emissions Reductions 8

2.3 A State-Led Decarbonization: Electricity Emissions Surge and Spark Carbon Redistribution 10

2.4 Deciphering Strategies: Committed Regions Pursue Distinct Decarbonization Paths While Integrating DAC and Renewables 13

2.5 The Silent Players: Uninvolved Regions Adhere to Expectations, but Emerge as Crucial for Federal Decarbonization 18

2.6 Despite Technology Deployment Distinctions, Costs Vary Little 20

Chapter 3: Discussion & Policy Implications 22

3.1 Key Findings 22

3.2 Policy Implications 24

3.3 Conclusion 26

Chapter 4: Methods 27

4.1 Temoa 27

Chapter 5: Acknowledgements 29

References: 30

Appendix: 34

LIST OF TABLES

Table 1 Political Indicator Inventory 5

Table 2 Regional Clustering by Decarbonization Amount 5

LIST OF FIGURES

Figure 1 Net-Zero Ambition States within the State Action Modeling Scenario 5

Figure 2 Cumulative Emissions by Scenario, Nationwide 5

Figure 3 Differences in CO_2 Emissions by Sector 5

Figure 4 Electricity Generation Difference 5

Figure 5 Net Electricity Imports in 2050 – Transmission Scenario Differences by Exporting Region 5

Figure 6 Carbon Management by Method 5

Figure 7 Transportation Sector Fuel Use Difference 5

CHAPTER 1 - INTRODUCTION

1.1 The Rise of Bottom-up Decarbonization Strategy

As the United States and other member countries to the Paris Climate Agreement undergo annual emissions stocktakes, greenhouse gas (GHG) reductions continue to fall short of levels necessary to meet radiative forcing goals.[1,2] 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.[3] 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 has set the United States' contribution to this goal at an ambitious 50% reduction in GHG emissions from 2005 levels by 2030. In comparison to global trajectories, the U.S. achieved a 17% reduction from 2005 levels in 2021, indicating progress toward this goal. The 2022 Inflation Reduction Act (IRA) bolsters 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 current administration's support for deep decarbonization is high, further federal action is uncertain and analysis suggests that the IRA alone is insufficient to meet the U.S. NDC targets.[4–6] The Trump Administration operated in stark contrast only a few years ago, with a core tenet of introduced Executive Orders being to curtail "government overreach."[7] Though the impacts of Trump's rollbacks are debated in their severity[7–11], 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. Compounded by an increase in gridlock and polarization of Congress, both the durability and the prospect for expansion of climate or energy legislation through the federal pipeline is in doubt. 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 U.S. 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.[12] The urgency of climate projections, the risk of technological lock-in, and strong citizen support thus turns the current question from when we will decarbonize, to how.

As of late, the answer to this appears to stem from the concepts of climate federalism and polycentrism within the policy literature. Similar in theoretical underpinning and different in scope of application, climate federalism arose as an academic subject of interest in the U.S. 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 fact, academic interest in environmental policy at the state level is nearly at a 30-year peak.[13] Often to gain a competitive advantage, it is not uncommon for states to take early action.[14] 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 says "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 faster-growing segments of this new economy. We should jump at the chance."[14] 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 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.

Complementing the “bottom-up” thinking of climate federalism is polycentrism, popularized in the climate governance context by political theorist Elinor Ostrom in the late 2000s.[15] Originally developed to explain small-scale collective action problems, polycentric orders are defined as “one where many elements are capable of making mutual adjustments for ordering their relationships with one another within a general system of rules where each element acts with independence of other elements.”[16] Centered around themes of “clumsiness” and the “direction of travel” rather than explicit, high-level objectives, polycentrism places focus on taking advantage of the institutional, technological, economic, and political capacities of subnational entities.[17] As the past decade has progressed, state-level climate and energy legislation has grown, allowing these subnational groups to utilize their capacities in more effective ways than the previously postulated “top-down” thinking. In 2023, there were twenty-four states plus the District of Columbia with specific adopted GHG emission targets.[18] Thirty-three states as of 2023 have released a climate action plan.[18]

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, we conduct a two-scenario modeling exercise using a comprehensive energy system optimization model (ESOM). The initial scenario 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 homogenous, nationwide emissions constraint for the second scenario.

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).

1.2 Energy Systems Optimization Modeling of Decarbonization Pathways

Energy system optimization models have emerged as the predominant model type for energy systems analysis over the past decade.[19] 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.[19] 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 gasses 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 literature 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, Hultman et al. explore the expanding role of subnational entities in a U.S. decarbonization. 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.[20] 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.[21] 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 24.4% to 44.3% by mid-century. Of note in this study was the sectoral competition between the building and transport sector 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.[22]

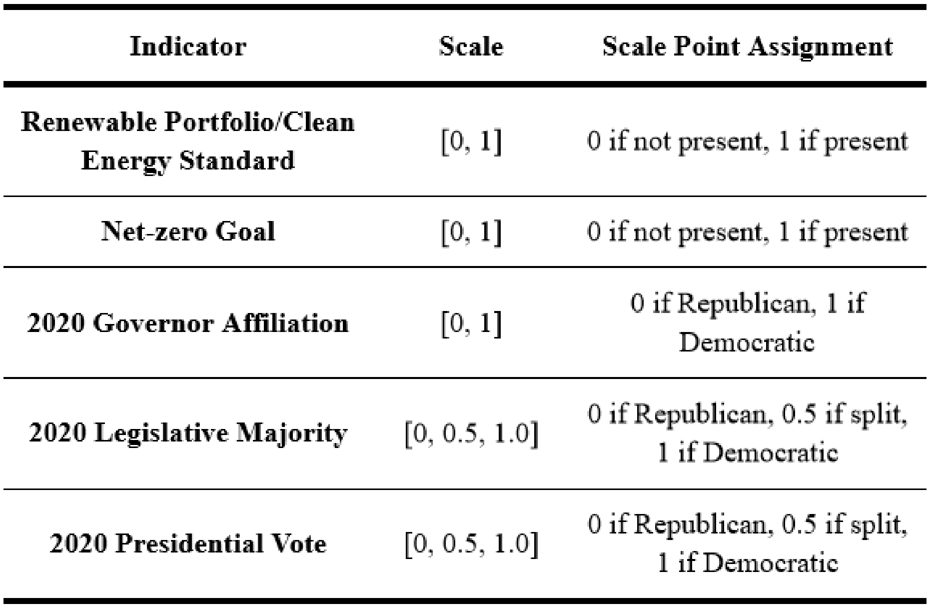
While Peng et al. examines heterogeneous decarbonization through emissions reduction constraints, lesser insight is provided on the nuances of capacity expansion and technology deployments. In contrast, our paper navigates the intersection of Peng and Hultman's work. Unlike Hultman's focus on strengthened subnational decarbonization or Peng's specification of decarbonization amounts, this study uses the ESOM Temoa to explore the detailed and context-specific technology selections necessary for multisectoral, state-led U.S. decarbonization. We employ policy to govern model-end emissions reductions and isolate the heterogeneity question. Our federal action scenario is not supplementary but rather substitutive.

CHAPTER 2 - RESULTS

2.1 Policy Scenario Design

Within this analysis, we are not modeling to see which policies are most effective at decarbonizing the U.S. economy. Instead, we are looking at the impact of governance level on decarbonization strategy. 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. For states identified as most amenable to climate policy, we introduce a CO_2 emissions constraint that linearly decreases until net-zero CO_2 emissions are achieved in 2050. This approach is representative of the array of carbon cap policies frequently considered in decarbonization scenarios.

Table 1. Political Indicator Inventory



Indicator	Scale	Scale Point Assignment
Renewable Portfolio/Clean Energy Standard	[0, 1]	0 if not present, 1 if present
Net-zero 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 Presidential Vote	[0, 0.5, 1.0]	0 if Republican, 0.5 if split, 1 if Democratic

We identify potential net-zero states using a set of five political indicators (presented in Table 1): the adoption of a state-level Renewable Portfolio Standard/Clean Energy Standard, a net-zero goal, the political affiliation of the governor and legislative majority, and the presidential vote. With a maximum possible score of five, a score of at least 3.0 is set as the binary threshold for states with 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 Figure 1. Initial CO_2 emissions rates were then obtained from the Energy Information Administration and used for the 2020 model base year.[23] We then assigned unique CO_2 emissions constraints to each of the nine TEMOA model regions based on the presence of net-zero states and their 2020 baseline emissions. Regional aggregation of these reductions were proportional to net-zero participation.

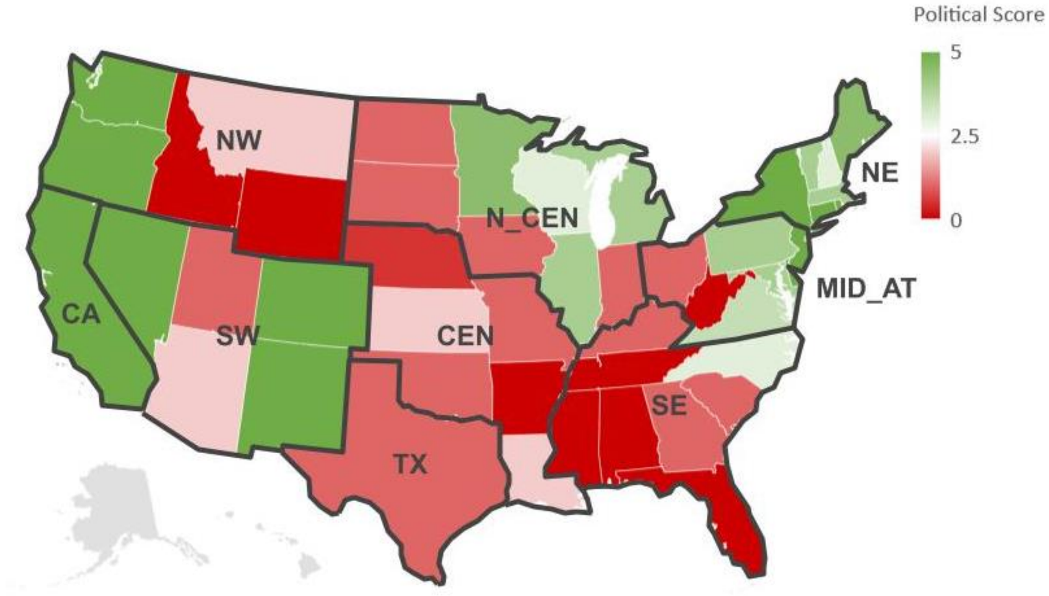


Figure 1. Net-Zero Ambition States within the State Action Modeling Scenario (HI & AK Excluded)

2.2 Scenario Emissions Reductions

Mid-century regional CO_2 emissions constraints for the State Action scenario ranged from 0% to 100%, as presented in Table 2. Implementation of these constraints in a Temoa model run yielded resultant regional emissions reductions from 1.6% (Central) to 100% (California & Northeast) in 2050. Overall, the State Action scenario yielded a 45.7% nationwide CO_2 emissions reduction, displayed in the left bars of Figure 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. Each region's respective CO_2 emissions reduction in each scenario is presented in the Supporting Information (SI).

Table 2. Regional Clustering by Decarbonization Amount

Net-Zero Potential	Regions Included	2050 Emission Constraints, State Action
High	California	100%
	Northeast	100%
Mixed	North Central	63.9%
	Mid Atlantic	63.6%
	Northwest	53.1%
	Southwest	54.2%
Low	Southeast	13.1%
	Texas	0.00%
	Central	0.00%

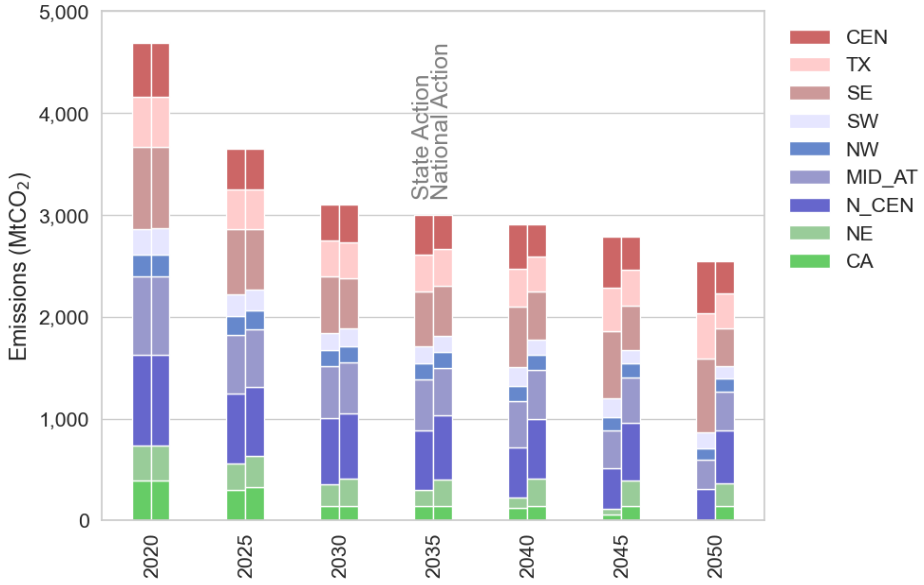


Figure 2. Cumulative Emissions by Scenario, Nationwide

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 comparison of electricity generation between scenarios. A detailed review of scenario changes in transmission quantity, carbon management practices, and primary energy consumption follows. Finally, scenario costs are provided for insight into cost-technology tradeoffs. To aid in interpretation of results, we categorize regions using a "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.

2.3 A State-Led Decarbonization: Electricity Emissions Surge and Spark Carbon Redistribution

Though aggregate national CO_2 emissions are identical between the State and National Action scenarios, as shown in Figure 2b, we see substantial shifts in where emissions occur. Figure 3 shows the emissions differences between scenarios, segmented by sector. 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.

While the two scenarios yield the same overall CO_2 emissions, 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. Spatial and sectoral disbursement also varies substantially. Nationwide, we see a sectoral redistribution of CO_2 of 439 $MtCO_2$ in 2050, 17.2% of total emissions for this time period. The additional emissions that occur in the State Action scenario solely arise from the electric sector. Under the National Action scenario, the additional CO_2 emissions span all other sectors, with the High and Mixed regions not directly constrained to address their hardest to abate emissions.

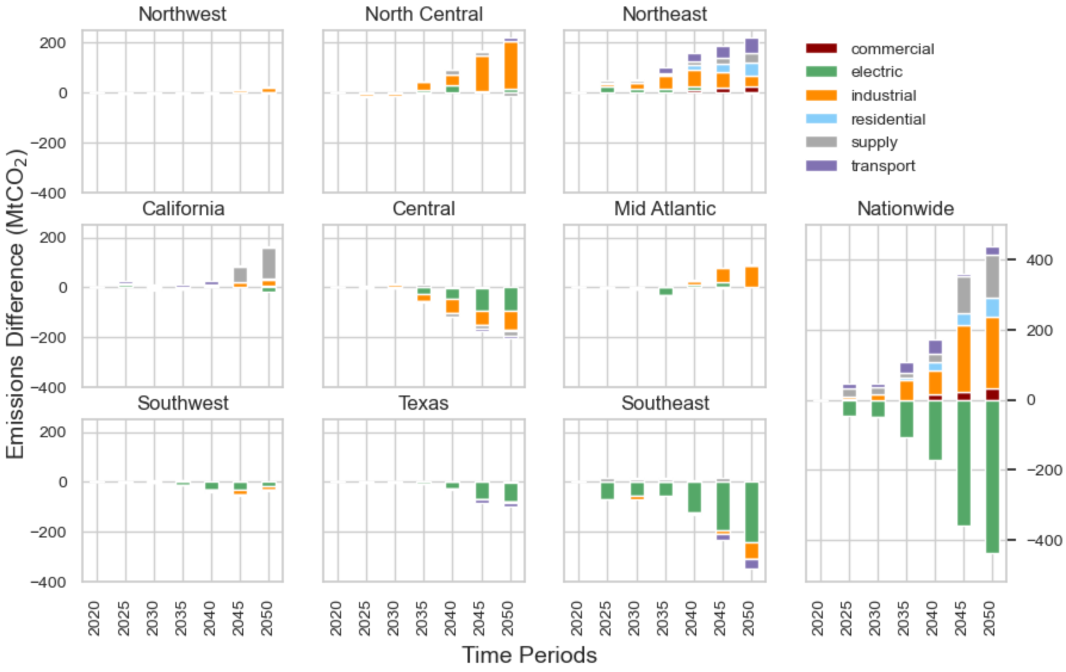


Figure 3. Differences in CO$_2$ Emissions by Sector. Positive values indicate higher emissions in the National Action scenario, while negative values indicate higher emissions in the State Action scenario.

To explore these emissions shifts further, Figure 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 – increase emissions consistently in the State Action scenario. Among these regions, the Southeast has the greatest increase in State Action emissions, with 349 MtCO$_2$ higher emissions in 2050 as compared to the National Action scenario. This suggests that the Southeast can provide cost effective mitigation under a national carbon mitigation program. As Figure 2a 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$_2$ emissions between scenarios. The North Central region diverges from the other Mixed-involvement regions, in which 2050 National Action emissions are roughly 200 $MtCO_2$ higher, driven by the industrial sector. High-involvement regions (i.e., California and the Northeast) fully achieve net-zero by 2050 in the State Action scenario. Alleviating the binding net-zero constraints for these regions, as is done in the National Action scenario, results in more cost-effective mitigation options pursued in other regions. California and the Northeast emit 146 $MtCO_2$ and 220 $MtCO_2$ in the National Action scenario's 2050 model time period, respectively. California does this primarily within the supply sector, which represents shifts in upstream fuel selection.

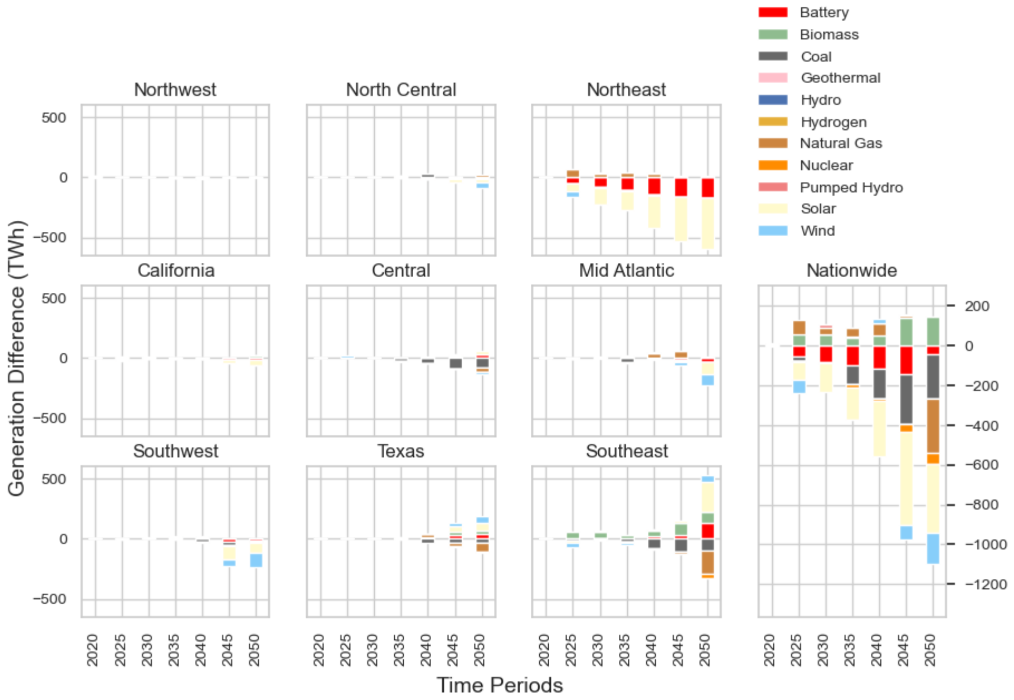


Figure 4. Electricity Generation Difference. Positive values indicate higher generation in the National Action scenario, while negative values indicate higher generation in the State Action scenario.

Low involvement regions pursue higher emitting options when unconstrained in the State Action scenario. Within the State Action scenario, the 439 $MtCO_2$ additional 2050 emissions from the electric sector comes predominantly from the low-involvement cluster regions, with the Southeast, Central, and Texas regions adding 243, 95, and 79 $MtCO_2$ in State Action electric sector emissions, 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. This is driven by the regional heterogeneity in CO_2 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, the region instead selects natural gas and coal.

Under the State Action scenario, we see a substantial increase in overall electricity generation. In 2050, this additional generation amounts to 952 TWh relative to the National Action scenario, an increase of 15%. Because our modeling approach relies on endogenous technology selection to meet specified energy service demands, we see that ambitious regional targets for decarbonization drive increased reliance on the electric sector by mid-century.

2.4 Deciphering Strategies: Committed regions pursue 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, rely on different power generation strategies and the use of carbon management through direct air capture (DAC) to different ends. The Northeast invests heavily in solar and storage, increasing solar generation by 418 TWh and installed battery storage by 173 TWh in 2050. California is projected to add far less new renewable energy, increasing solar generation 47 TWh beyond 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 is projected to experience a notable increase in the import of electricity from the Southwest, importing an additional 207 TWh in the State Action scenario. This corresponds with a similar increase in solar and wind generation in the Southwest region. Net imports from the Southwest to California almost doubled, from 251 TWh in the National Action scenario to 460 TWh in a state-led scenario. California's own in-region generation is 338 and 385 TWh for the National and State Action scenarios, respectively, in 2050. In a state-led decarbonization, California's most cost-effective strategy is to augment renewable electricity through imports from the Southwest, rather than relying on in-house generation.

Regarding transmission differences, beyond the high-involvement regions, the mixed-involvement North Central region experiences an increase in electricity imports in the State Action scenario. In 2050, the North Central region imports 192 TWh from the Central region while contributing minimal exports during the same period. Consequently, the North Central region consumes approximately 20% more electricity than it generates in 2050. While California's net-zero policy spurs solar and wind deployment in the Southwest, the North Central region's imports from the Central region correspond to additional coal (81 TWh) and natural gas (33 TWh) generation. Though Central wind generation also increases slightly (18 TWh), acknowledging these increases in fossil fuel generation shows risk of emissions leakage. By magnitude, the North Central's State Action scenario requires the greatest emissions reduction of any region relative to present day emissions (579 $MtCO_2$), indicating that 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.

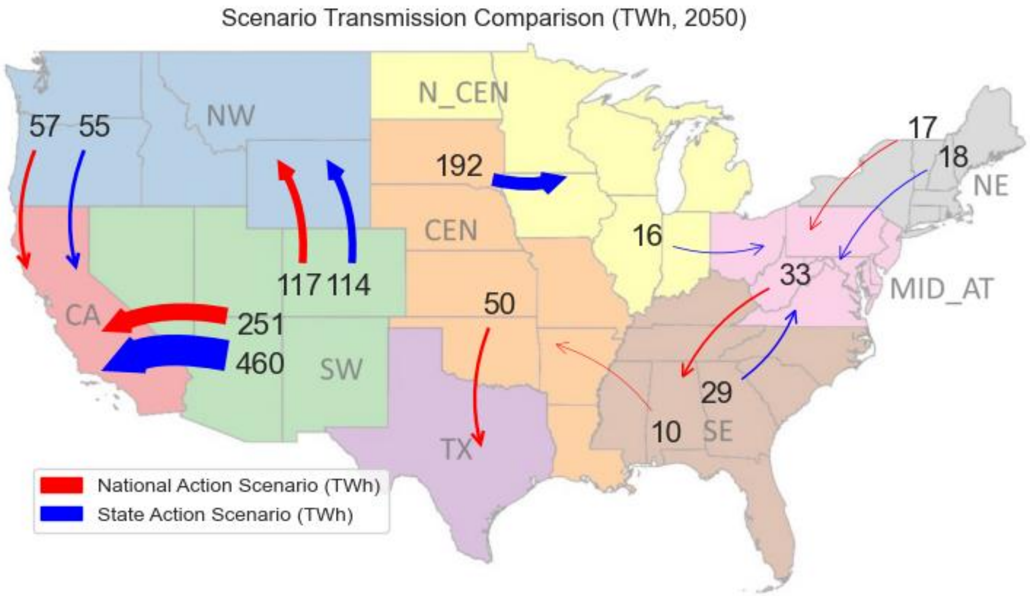


Figure 5. Net Electricity Imports in 2050 - Transmission Scenario Differences by Exporting Region

Transitioning from the examination of power sector generation disparities and shifting focus to 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 Figure 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 $MtCO_2$ in 2050, as compared to the National Action scenario, ultimately being used for synthetic transport fuels (Figure 7). This removal amount represents 35% of the emissions difference between the State (0 $MtCO_2$) and National Action (221 $MtCO_2$) final 2050 emissions. In California, DAC with geologic storage offsets an additional 116 $MtCO_2$ and DAC to fuels accounts for 15 $MtCO_2$ in the State Action scenario's 2050 model time period. Combined, these DAC technologies account for 90% of the emissions difference (146 $MtCO_2$) between California's scenarios in 2050. Both regions take advantage of DAC, but to different ends. In part, this difference in end use arises from Temoa's modeled geologic sequestration potentials. While California has a modeled 29.8 $GtCO_2$ storage potential, the Northeast is permitted only 0.4 $GtCO_2$.

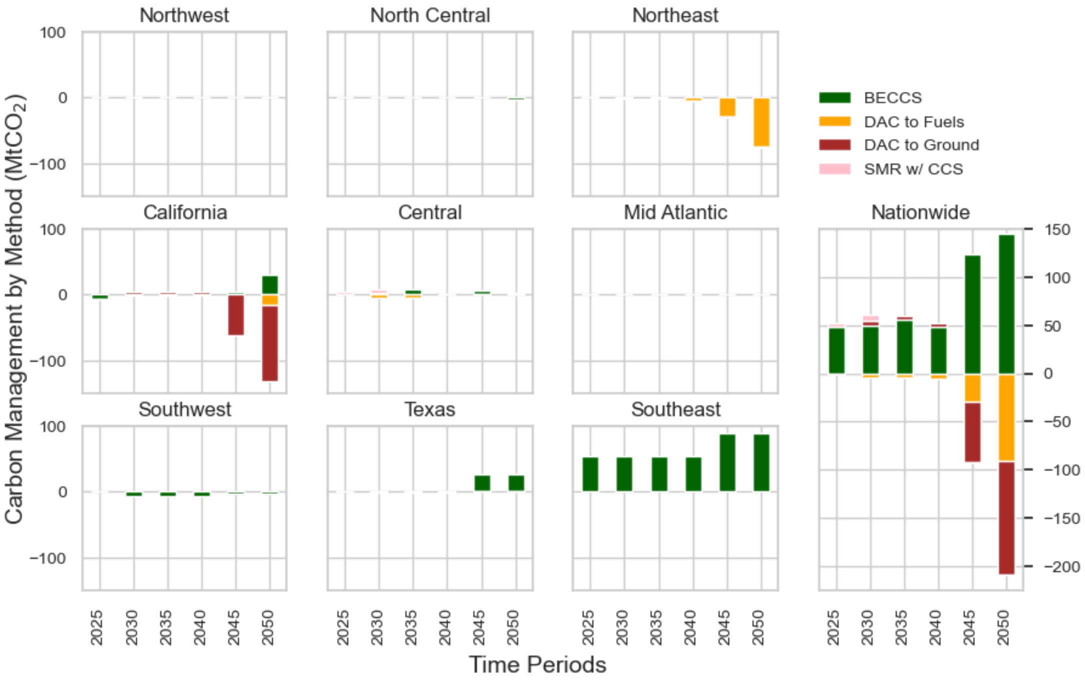


Figure 6. Carbon Management by Method. Positive values indicate higher management in the National Action scenario, while negative values indicate higher management in the State Action scenario.

For the transportation sector, we see increased use of electricity and novel fuels in scenarios which require deeper decarbonization for any given region. Figure 7 shows that, when many regions engage in emissions reduction, they rely on the transport sector for some amount of that reduction. High-involvement regions within the state-led scenario seek lower-emission fuels than the federally-led scenario. Added fuel use in the National Action scenario for California and the Northeast included jet fuel, gasoline, diesel and other fossil fuels. 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. Low-involvement regions experience their own shift, though in the opposite direction between scenarios. In the State Action scenario, the Southeast, Texas, and Central regions rely more heavily on diesel and gasoline. 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 oft-increased in the State Action scenario, such as 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. 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.

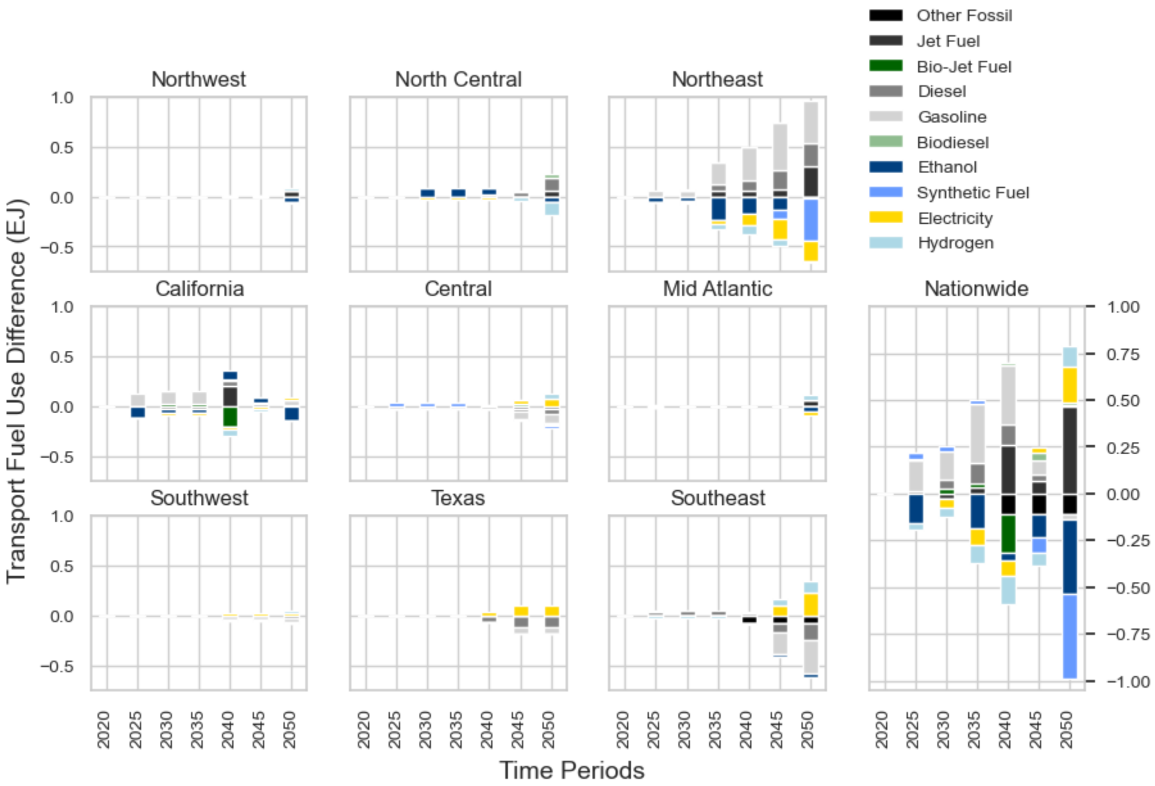


Figure 7. Transportation Sector Fuel Use Difference, Positive values indicate higher fuel use in the National Action scenario, while negative values indicate higher fuel use in the State Action scenario.

2.5 The Silent Players: 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 & sequestration (BECCS) proves to be a cost-effective alternative to direct air capture. As shown in Figure 6, the Southeast deploys considerable amounts of BECCS in the National Action scenario. In 2050, this 89 $MtCO_2$ of additional BECCS deployment accounts for 25% of the 349 $MtCO_2$ emissions reduction in the Southeast’s National Action scenario as compared to State Action.

Perhaps of more interest than BECCS deployment in isolation, though, is the context in which this deployment occurs. The Southeast's emissions reduction over the entire study period in the State Action scenario is 80 $MtCO_2$, equivalent to a 9.9% decrease. National Action scenario reductions were far greater at 429 $MtCO_2$, equivalent to a 53.3% decrease. Within a federally-led decarbonization effort, the Southeast region is responsible for the greatest overall reduction in emissions, exceeding the absolute levels of emissions reduction of both high-involvement regions, California and the Northeast, in the State Action scenario (394 and 345 $MtCO_2$). 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 National Action. Beyond BECCS, we see that the Southeast also decarbonized its electricity generation under the National Action scenario (Figure 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 an additional 199 TWh of electricity generation for transportation electrification. 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. While the region does not yield a relative decarbonization rate as large as the State Action scenario's high-involvement cluster, the magnitude of decarbonization is greater than either of the high-involvement regions' State Action reductions. 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.

2.6 Despite Technology Deployment Distinctions, Costs Vary Little

While the State and National Action scenarios result in substantially different technology deployments and substantial regional fuels shifting, system cost differences are low. The system-level discounted fixed, investment and variable costs are provided in the Supporting Information, 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 $40.20T for the State Action scenario and $39.92T for the National Action scenario, relying on state-level decarbonization policies increases energy system costs by 0.7% relative to a nation-wide least-cost pathway.

While the overall cost differences are minor, we observe more substantial regional differences, also shown in the Supporting Information. 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. These Northeast and Central region State Action scenario cost increases are 4.3% and 3.3% respectively 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 results 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.

CHAPTER 3 – DISCUSSION & POLICY IMPLICATIONS

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.[14] Advocacy groups have recently called for a multi-tiered government collaboration, aptly named "New Climate Federalism," which recognizes the strengths of each government level.[24] However, a changing administration could readily affect the passing of climate-friendly energy policy. As of the writing of this paper, an upcoming presidential election sets two vastly different federal energy policy landscapes against each other. One party celebrates existing renewable energy tax incentives, forthcoming vehicle emissions mandates from the EPA, and U.S. participation in the Paris Agreement as hallmarks of achievement, while the other explicitly targets their removal. For this reason, a piecemeal approach to decarbonization using the strengths of the states may offer the most resilient pathway for further reductions in emissions. This study seeks to answer what that decarbonization endeavor may look like and generates key insights for policymaking in doing so.

3.1 Key Findings

First and foremost, our results support existing literature surrounding the need for electrification in 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. Furthermore, they 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. 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_2/kWh, while a federally-driven power sector has eight times less at 5.7gCO_2/kWh. 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_2/kWh.[25]

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-emissions generation for residential 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 demonstrates the need for energy policy designed to play to both a region's strengths and needs.

This notion of playing to the strengths of U.S. 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 unmotivated regions into significant contributors. 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 GDPs.[26] It should be noted that these costs may not even be truly borne by them, as it is the structural methodology of Temoa which assigns costs to producing regions.

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.[27,28] Beyond just their importance in deep-decarbonization, the Southeast’s involvement in a mid-century, deep decarbonization may require a seven-fold increase in raw biomass feedstock production, represented by a growth in biomass shares from 8% of U.S. production in 2020 to 20% in 2050.[28] Given both scenarios had CO_2 emissions reductions of 45%, 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.

3.2 Policy Implications

The extreme technological sensitivity of the U.S. 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 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 inexpensive 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.

Summarily, 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 federalist energy transition is inherently inefficient, slow, and more costly. Instead, it suggests a decarbonization pathway where expenses might be borne by the politically willing. With the exception of the previously mentioned Central region leakage issue, the state-led scenario displays a clear output: Those interested in decarbonization will pay for it. 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.

That said, the National Action scenario is still useful as a guide to where future federal intervention is best placed. 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 necessary to achieve deeper decarbonization objectives, yet these resources are projected to remain unused without additional federal 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 Biomass Crop Assistance Program (BCPA) 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 GDP, 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 greatest bipartisan support as compared to mandates and standards.[29]

3.3 Conclusion

While U.S. decarbonization will likely be driven by state ambition, our results indicate that this pathway will be substantially different than a collective decarbonization. However, system costs nationwide will be near-identical to its homogenous 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. Ultimately, we find moderate emissions reductions from stylized subnational action, unable to meet larger stated federal ambitions. As a result, we suggest this paper's National Action scenario be a means to identify where federal intervention may be most cost-effective and politically resilient. The disconnect between 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.

CHAPTER 4 - 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_2 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.

4.1 Temoa

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. 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. Designed as a least-cost linear optimization program, it minimizes total system cost over the user-specified time horizon under system-level and user-defined constraints. The algebraic formulation may be found in Hunter et al.[30], while updates to Temoa are provided in a GitHub Repository.[31] Previous studies that relied on Temoa include those by DeCarolis et al., de Queiroz et al., Patankar et al. and Bennett et al.[32–35]

For this analysis, the time horizon spans 2020 to 2050 in 5-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. Results are solved myopically rather than with perfect foresight, with nine US regions: Northwest, California, Southwest, North Central, Central, Texas, Northeast, Mid Atlantic, and Southeast. Model regions are chosen for their similarity in aggregation to US electric balancing authorities while following state boundaries.

CHAPTER 5 – ACKNOWLEDGEMENTS

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APPENDIX

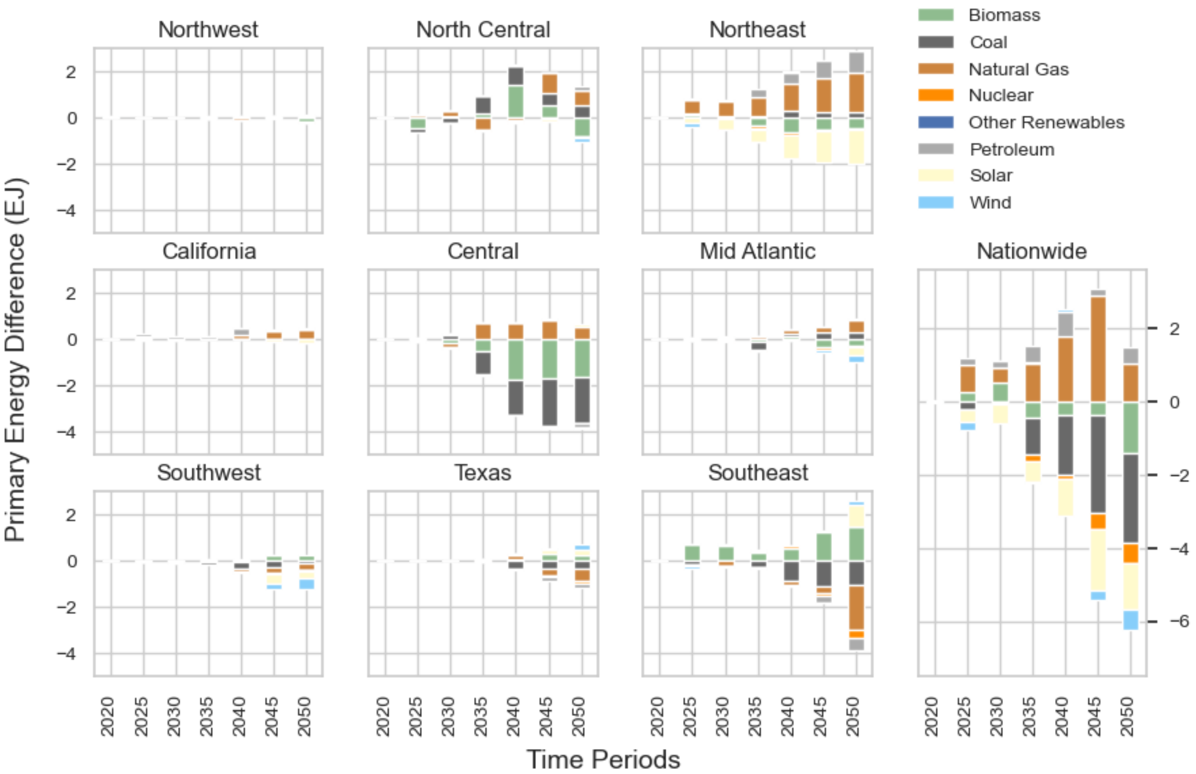


Figure A1: Primary Energy Difference by Fuel. Positive values indicate higher primary energy use in the National Action scenario, while negative values indicate higher primary energy use in the State Action scenario.

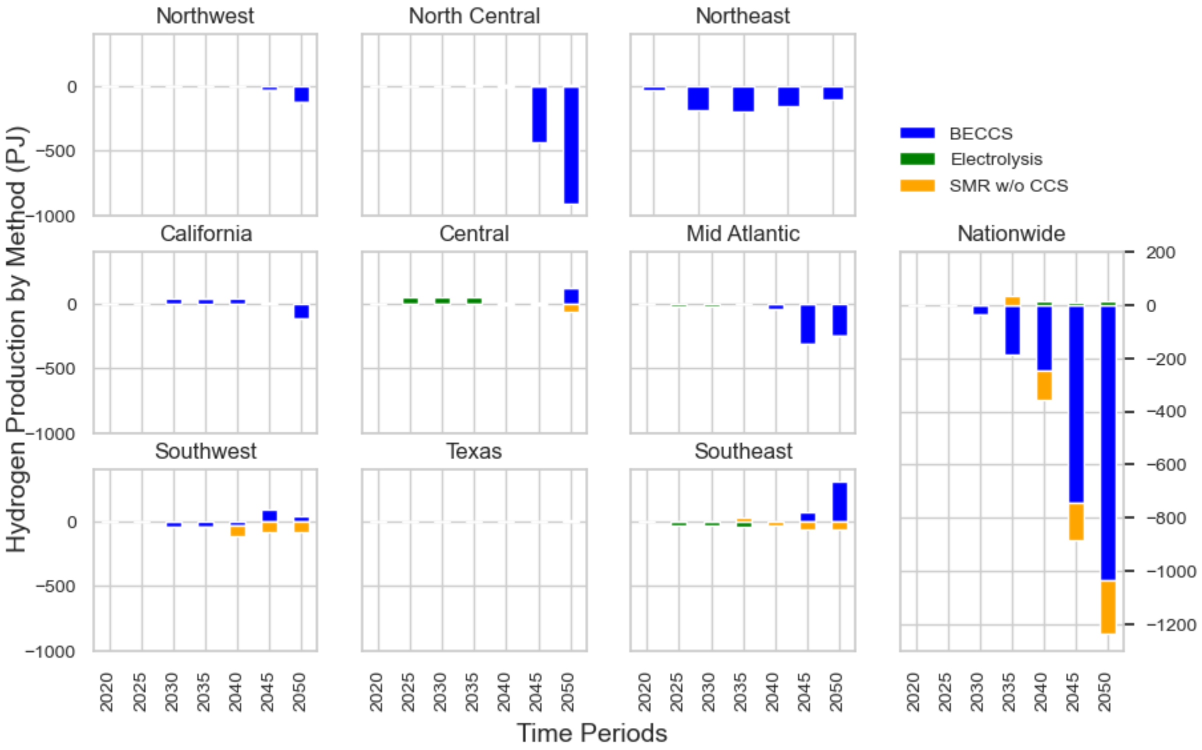


Figure A2: Hydrogen Production by Method. Positive values indicate higher hydrogen production in the National Action scenario, while negative values indicate higher hydrogen production in the State Action Scenario.

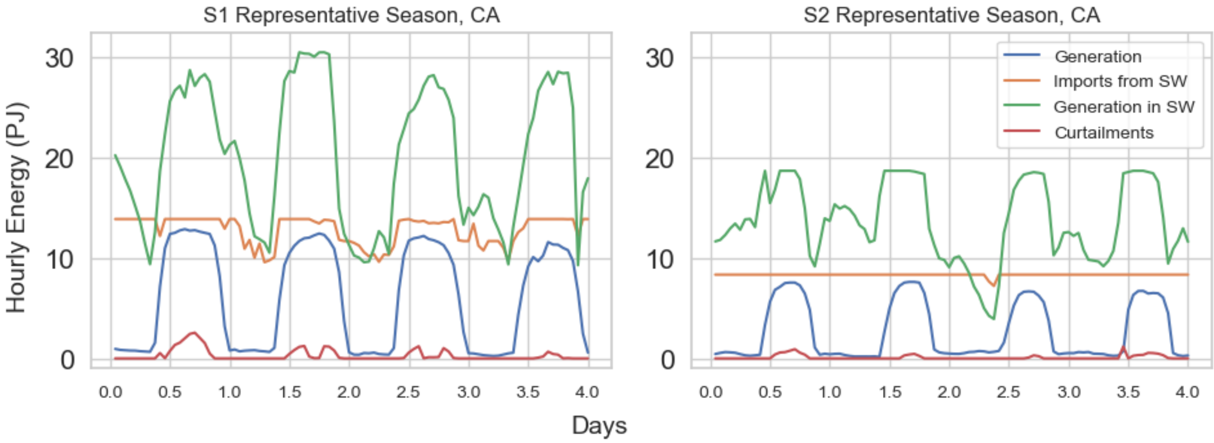


Figure A3: California 2050 Representative Days, Generation of Solar + Wind

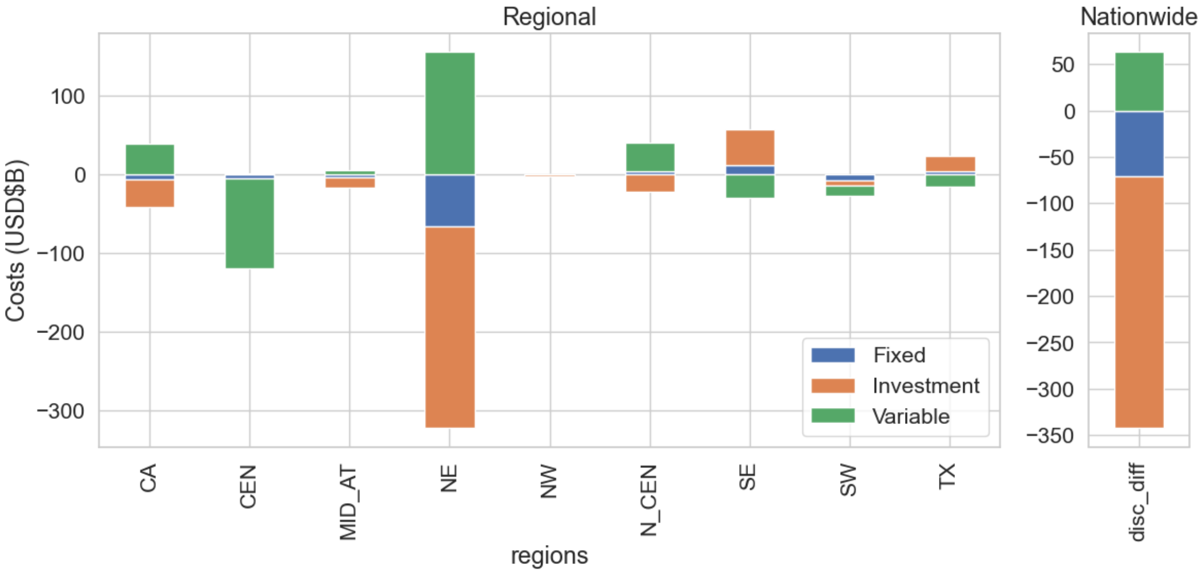
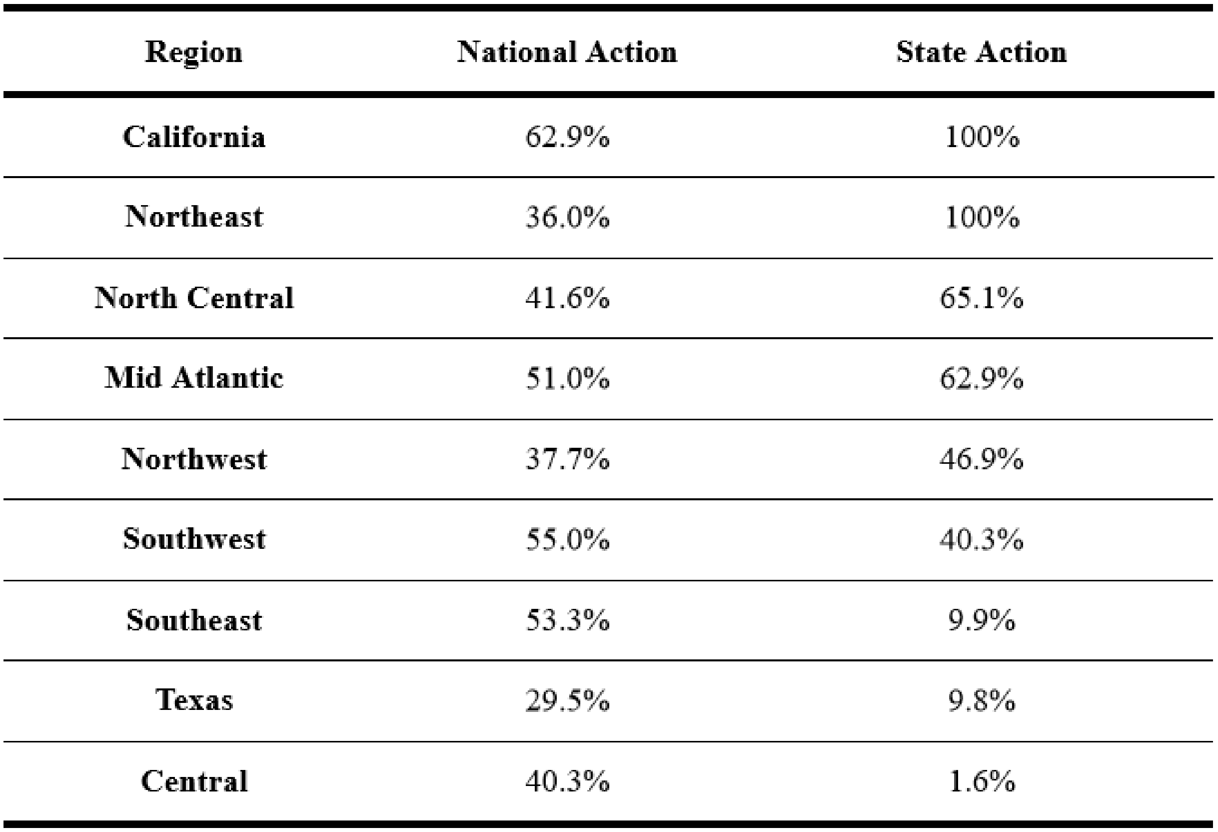
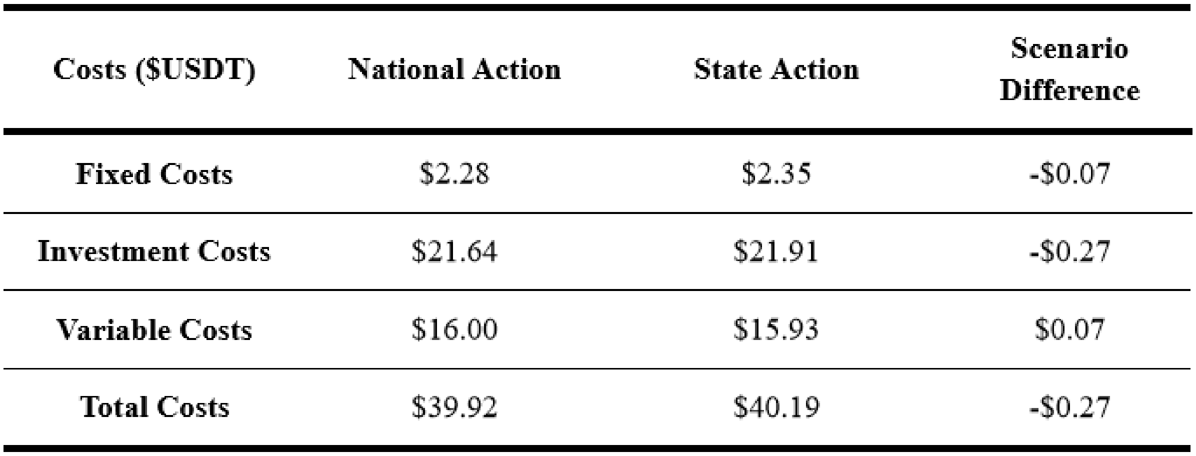


Figure A4: Regional Cost Differences. Positive values indicate higher costs in the National Action scenario, while negative values indicate higher costs in the State Action scenario.



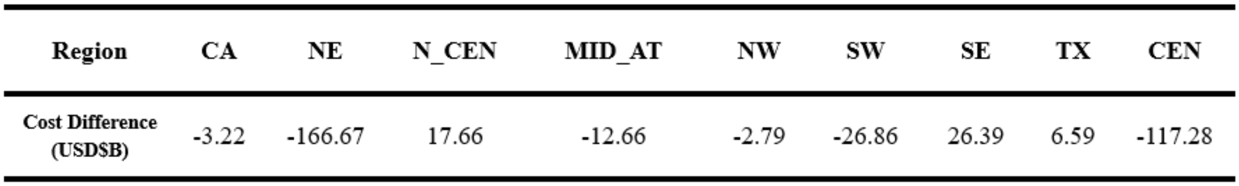
Region	National Action	State Action
California	62.9%	100%
Northeast	36.0%	100%
North Central	41.6%	65.1%
Mid Atlantic	51.0%	62.9%
Northwest	37.7%	46.9%
Southwest	55.0%	40.3%
Southeast	53.3%	9.9%
Texas	29.5%	9.8%
Central	40.3%	1.6%

Figure A5: Real CO$_2$ Emissions Reductions by Scenario



Costs ($USDT)	National Action	State Action	Scenario Difference
Fixed Costs	$2.28	$2.35	-$0.07
Investment Costs	$21.64	$21.91	-$0.27
Variable Costs	$16.00	$15.93	$0.07
Total Costs	$39.92	$40.19	-$0.27

Figure A6: Discounted Fixed, Investment and Variable Costs



Region	CA	NE	N_CEN	MID_AT	NW	SW	SE	TX	CEN
Cost Difference (USD$B)	-3.22	-166.67	17.66	-12.66	-2.79	-26.86	26.39	6.59	-117.28

Figure A7: Raw and Relative Discounted Investment Differences, by Region