

Supplementary Information for:

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

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Supplementary Methods

Description of the main constraints: In this section, we first provide a more detailed description of the model formulation for Temoa, particularly as it relates to the model's objective function and constraints. This formulation and description is based on Blackhurst et al., which relies on a similar approach to address different research questions related to the U.S. energy system. Temoa is a linear capacity expansion optimization model in which the U.S. energy system is represented as a network of interlinked technologies & commodities. Parameters included to represent added capacity include investment costs, fixed costs, technology lifetime, generation efficiency and other parameters. Core components of Temoa are the set decision variables, the objective function relevant, and constraints added to incorporate real-world considerations.

Temoa optimizes the deployment and dispatch of energy technologies on the basis of satisfying exogenous end-use demands across the energy system. In the context of electricity generation, decision variables are the capacity added for any relevant generation technology, and its hourly dispatch. Our objective function is to achieve minimum system-wide costs of the energy supply while meeting all specified demands under specified constraints. Supplementary Equation 1 provided shows the objective function which minimizes the energy supply costs across the system. Accounted for within this equation are three cost components, shown in Supplementary Equations 2, 3 and 4. Those are fixed costs (Supplementary Equation 2), annualized investment costs (Supplementary Equation 3), and variable costs (Supplementary Equation 4). Within these equations, CAP represents capacity of a technology and FO represents the associated activity of said technology.

$$\text{Min } C_{total} = \text{Min}(C_{fixed} + C_{loans} + C_{variable}) \quad (1)$$

$$C_{fixed} = \sum_{r,p,t,v} \left(\frac{CF_{r,p,t,v} \cdot ((1+GDR)^{P_0-p+1} \cdot (1-(1+GDR)^{-MPL_{r,t,v}}))}{GDR} \cdot CAP_{r,t,v} \right) \quad (2)$$

$$C_{loans} = \quad (3)$$

$$\sum_{r,t,v} \left(\frac{CI_{r,t,v} \cdot LA_{r,t,v} \cdot ((1+GDR)^{P_0-v+1} \cdot (1-(1+GDR)^{-LLP_{r,t,v}}))}{GDR} \cdot \left(\frac{1-(1+GDR)^{-LPA_{r,t,v}}}{1-(1+GDR)^{-LTP_{r,t,v}}} \right) \cdot CAP_{r,t,v} \right)$$

$$C_{variable} = \quad (4)$$

$$\begin{aligned} & \sum_{r,p,t,v} \left(\frac{CV_{r,p,t,v} \cdot ((1+GDR)^{P_0-p+1} \cdot (1-(1+GDR)^{-MPL_{r,p,t,v}}))}{GDR} \cdot \sum_{S,D,I,O} FO_{r,p,s,d,i,t,v,o} \right) \\ & + \sum_{r,p,t,v} \left(\frac{CV_{r,p,t,v} \cdot ((1+GDR)^{P_0-p+1} \cdot (1-(1+GDR)^{-MPL_{r,p,t,v}}))}{GDR} \cdot \sum_{I,O} FAO_{r,p,i,t \in T^a, v,o} \right) \end{aligned}$$

The subscripts shown represent sets including model regions (r), time periods (p), seasons (s), time of day (d), input commodity (i), technology (t), and output commodity (o). The indices (r, p, s, d, i, t, o) in the above

equations are drawn from sets defined in the model scope on the regions, technologies, time-period, vintage, season, time of day, input commodity, and output commodity, respectively. These indices are used to index various parameters and decision variables in the optimization problem. For example, the $CF_{r,p,t,v}$ parameter represents fixed operations and maintenance costs, while the r, p, t , and v indices indicate a particular combination of region, period, technology, and vintage. GDR is the global discount rate used to calculate present cost, P_0 is the start of the time horizon, r,t,v is the smaller of the remaining model horizon or process technology life, $CAP_{r,t,v}$ refers to the required technology capacity to support associated activity, $CI_{r,t,v}$ represents the technology-specific investment cost, $LA_{r,t,v}$ is the loan amortization by technology and vintage based on the discount rate of the technology, and $CV_{r,p,t,v}$ refers to the variable operations & maintenance cost. $LPA_{r,t,v}$ represents the active lifetime of process t in region r before the end of the model horizon, and $LTP_{r,t,v}$ represents the full lifetime of a regional process (r, t, v) . $FO_{r,p,s,d,i,t}$ is the commodity flow by time of day and season that flows out of a technology based on a given input, $FOA_{r,p,i,t}$ is similar to FO but only represent the annual commodity flow out of a technology, instead of representing flow in each time interval. This relaxation is applied to technologies that are not expected to experience much variation sub-annually and helps reduce the computational expense incurred while running the model. Finally, the main constraints that govern the flow of energy through the model network are as follows: (1) “Demand Constraint,” which ensures that the supply meets demand in all time intervals (S5), (2) “Capacity Constraint,” which ensures that sufficient capacity is available to meet the commodity flows in all time intervals for each chosen process in the model (S6), and (3) “Commodity Balance Constraint,” which ensures that global commodity production within the energy system is sufficient to meet the endogenous demands for that commodity (S7).

Demand Constraint:

$$\sum_{I, T-T^a, V} FO_{r,p,s,d,i,t} + SEG_{s,d} \sum_{I, T^a, V} FOA_{r,p,i,t} = DEM_{r,p,dem} \cdot DSD_{r,s,d,dem} \quad (5)$$

$FO_{r,p,s,d,i,t}$ and $FOA_{r,p,i,t}$ are defined above, $SEG_{s,d}$ is the fraction of the year represented by each (season, day) tuple, $DEM_{r,p,dem}$ are the end-use demands by region and time period, and $DSD_{r,s,d,dem}$ is the demand-specific distribution, which provides sub-annual demand variation.

Capacity Constraint:

$$(CFP_{r,t,v} \cdot C2A_{r,t} \cdot SEG_{s,d} \cdot PLF_{r,p,t,v}) \cdot CAP_{r,t,v} = \sum_{I, O} FO_{r,p,s,d,i,t,v,o} + \sum_{I, O} CUR_{r,p,s,d,i,t,v,o} \quad (6)$$

Within the above equation, $SEG_{s,d}$ and FO are defined above. $CFP_{r,t,v}$ is the capacity factor specific to a given process, $C2A_{r,t}$ converts capacity into activity, $PLF_{r,p,t,v}$ is the process life fraction active in time p , and $CUR_{r,p,s,d,i,t,v,o}$ is the commodity flow from a curtailed technology.

Commodity Balance Constraint:

$$\begin{aligned} & \sum_{I, T, V} FO_{r,p,s,d,i,t,v,o} + regFIM_{r-reg,p,s,d,i,t,v,c} = \\ & \sum_{T^8, V, I} FIS_{r,p,s,d,c,t,v,o} + \sum_{T^8, V, I} \left(\frac{FO_{r,p,s,d,c,t,v,o}}{EFF_{r,c,t,v,o}} \right) \\ & + SEG_{s,d} \sum_{r,c,t,v,o} \left(\frac{FOA_{r,p,c,t}}{EFF_{r,c,t,v,o}} \right) + \sum_{r-reg,p,s,d,c,t,v,o} FEX_{r-reg,p,s,d,c,t,v,o} + \sum_{r,p,s,d,i,t,v,c} FLX_{r,p,s,d,i,t,v,c} \end{aligned} \quad (7)$$

Supplementary Equation 7 is a balance of commodities, where the sum of production and imports must be equal to consumption, exports and excess for commodities system-wide. FO is commodity flow, FIM the imports, FIS is storage technology flow, FEX represents exports between regions for electricity or hydrogen, and FLX is the excess commodity production above demand. Beyond the constraints shown, additional constraints include network-related constraints and physical and operational constraints relating to storage, firm generation, ramping and reserve margins. Relating to emissions, an emission limit constraint is applied to the model through the commodity emissions set and a parameter tracking emissions activity, $EAC_{r,e,i,t,v,o}$. Supplementary Equation 8 provides the emissions limit equation. FO is previously defined as commodity flows, FOA is the annual commodity flow for annualized technology sets. An added set within emissions constraint is the region and time period-based emission limit (e). If assigned by the modeler, the emission limit provides an emission ceiling for each time period. The relevant sets as shown at the end of Supplementary Equation 8 are for all regions and time periods with a set emissions limit, with the theta superset notation simply indicating the constraint is only defined for the exact indices for which the modeler specified.

Emissions Constraint:

$$\begin{aligned} & \sum_{S,D,I,T,V,O|r,e,i,t,v,o \in EAC} (EAC_{r,e,i,t,v,o} \cdot FO_{r,p,s,d,i,t,v,o}) \\ & + \sum_{I,T,V,O|r,e,i,t \in T^a, v,o \in EAC} (EAC_{r,e,i,t,v,o} \cdot FOA_{r,p,i,t \in T^a, v,o}) \leq ELM_{r,p,e} \end{aligned} \quad (8)$$

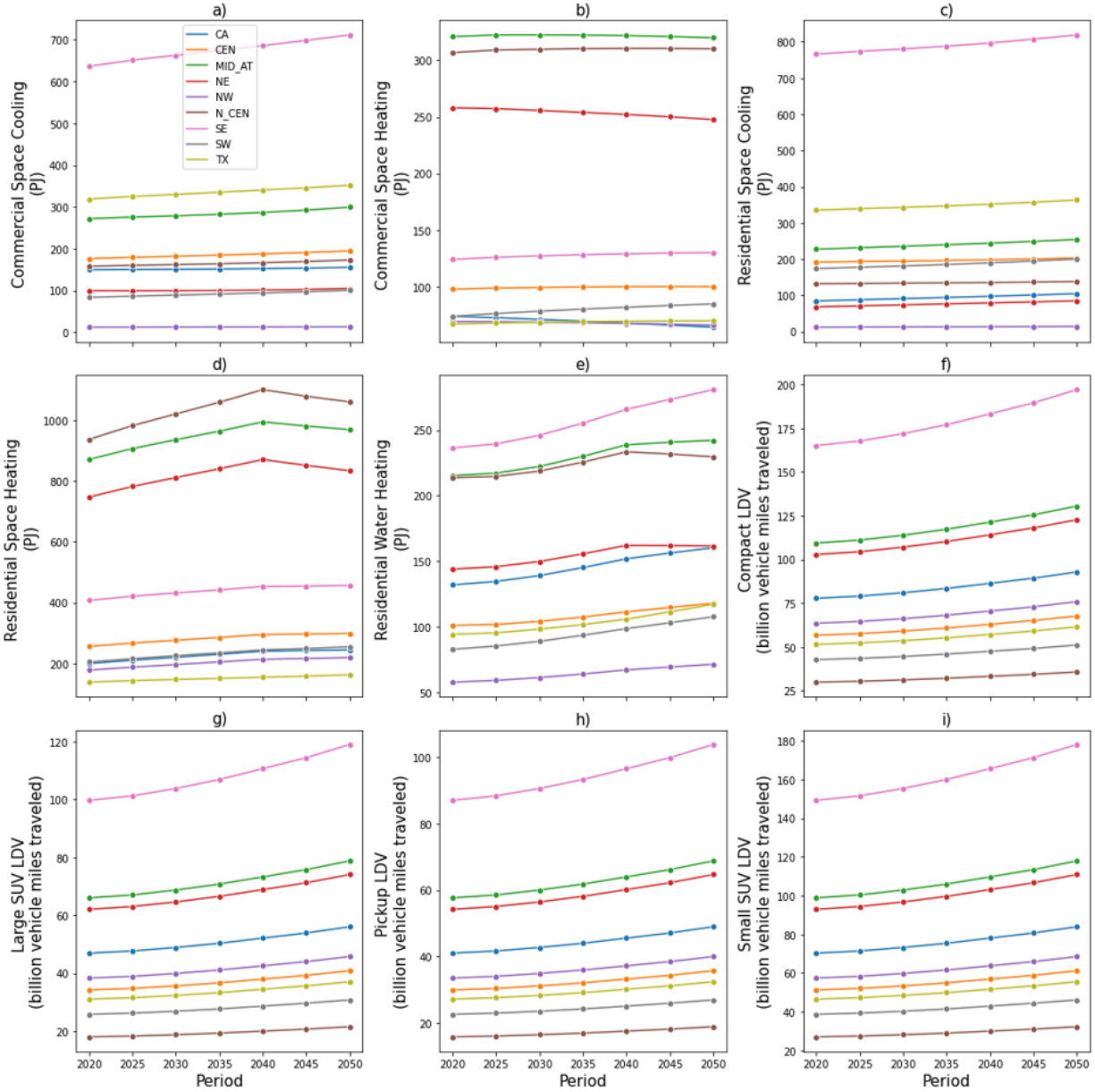
$$\forall \{r, p, e\} \in \theta_{EmissionLimit}$$

In addition to the provided mathematical representations of Temoa's model formulation, Table S1 provides cost, technology characteristic, supply, and other input data for the scenario model runs. This table also includes information regarding input assumptions for added cost considerations like the Inflation Reduction Act.

Supplementary Table 1. Database Assumptions, Inputs and Modeled Policy Constraints

Sector	Description
Fuel supply	Fossil fuel prices projections are exogenously specified from the Annual Energy Outlook Reference case. ¹
Electric	Input cost assumptions and performance characteristics for electric generators are from the National Renewable Energy Lab's (NRELs) Annual Technology Baseline, 2021. ²
Transportation	This sector includes four modes of transportation: road, rail, air and water. Efficiencies, demands and costs for these vehicles are derived from the nine-region MARKAL database produced by the U.S. Environmental Protection Agency (EPA), the NREL Electrification Futures Study's Moderate Advancement Scenario, and the study "Net-Zero America: Potential Pathways, Infrastructure, and Impacts, Final Report." ³⁻⁵ Road transportation includes light, medium and heavy-duty vehicles. The percent of end-use demand for each vehicle size class is exogenously specified.
Commercial	Service demands are included from the NREL Electrification Futures Study. ⁴ Existing technology capacities are from U.S EPA's nine-region MARKAL database, while

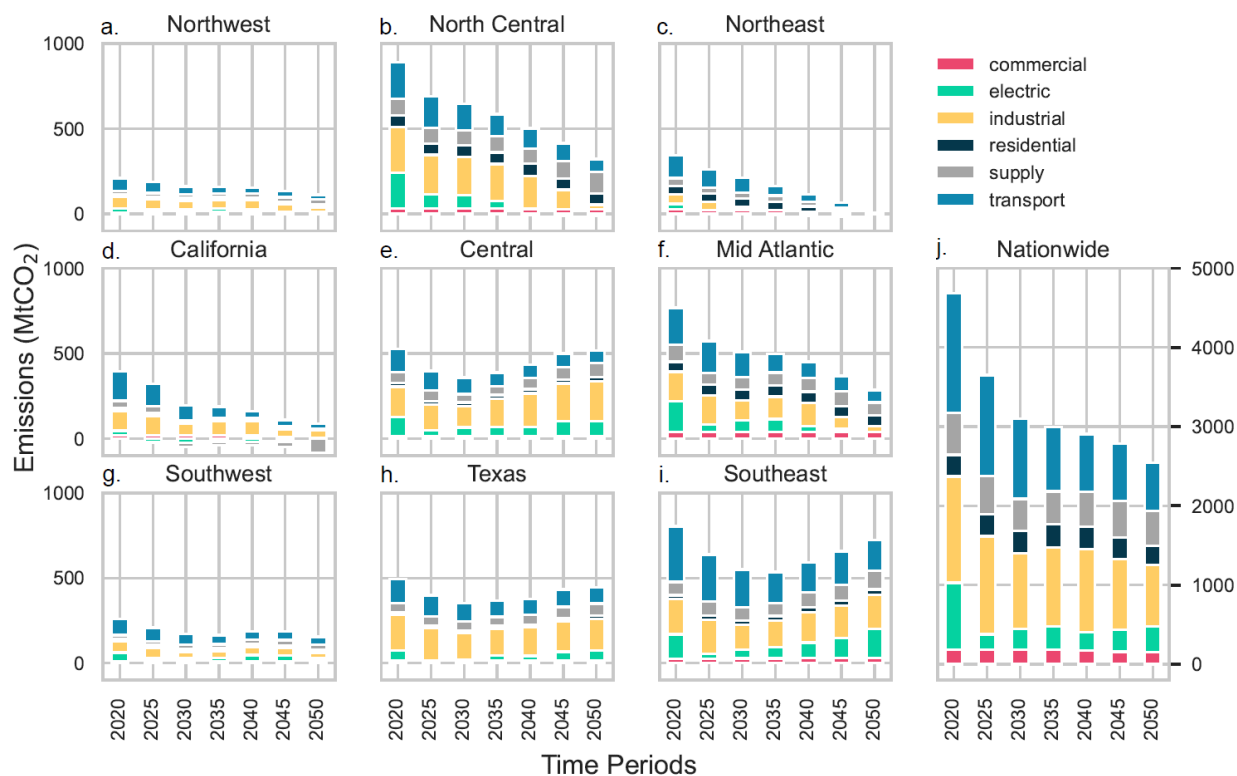
	techno-economic parameters of end-use technologies are from the EIA. Techno-economic characteristics for demand technologies are derived from the National Energy Modeling System - Updated Building Sector Appliance and Equipment Costs & Efficiency.^{3,6}
Residential	Service demands are included from the NREL Electrification Futures Study.⁴ Existing technology capacities are from the U.S. EPA's nine-region MARKAL database, while techno-economic parameters of end-use technologies are from the EIA. Techno-economic characteristics for demand technologies are derived from the National Energy modeling System - Updated Building Sector Appliance and Equipment Costs & Efficiency.^{3,6}
Industrial	End-use demands for the industrial sector are derived from the North American Industry Classification System. Demands are derived from the Manufacturing Energy Consumption Survey.⁷ Common industrial processes represent this sector's energy sector consumption, and include the following: Process heating, conventional boiler use, cogeneration systems, machine drivers, facility HVAC, process cooling and an 'other' energy-use.
Hydrogen	Cost and efficiency assumptions provided from the 2019 IEA Future of Hydrogen Report.⁸
Regional Boundaries	The U.S. is divided into nine regions, as provided in Figure 1.
CCS	Estimated BECCS technology efficiencies are derived from the averages across Integrated Assessment Models from Krey et al.⁹ Generation facility CCS efficiencies are from PowerGenome.
Fischer-Tropsch Fuels ¹⁰	Fischer-Tropsch fuel synthesis using H₂ and CO₂ is based on the techno-economic parameters discussed in Zang et al.
Direct Air Capture	Capital and fixed costs are from Keith et al., while CO₂ transport is modeled using Net-Zero Americas study cost curves.^{5,11}
Renewable Resources and Transmission Build Out	Renewables data is compiled from PowerGenome.¹² This is a Github which includes tools for creating input datasets for electric sector capacity expansion models. Capacity factors for brownfield renewables generation are obtained from EIA.
IRA Provisions	This database incorporates IRA provisions through modeled economic incentives. Modeled provisions include investment and production tax credits for renewable generation, carbon capture and consequent sequestration/use, production tax credits for existing nuclear, clean hydrogen tax credits, and electric passenger and commercial vehicle tax credits.
Discount Rate	A discount rate of 5% is assumed, with exceptions for technology-specific discount rates provided from PowerGenome.



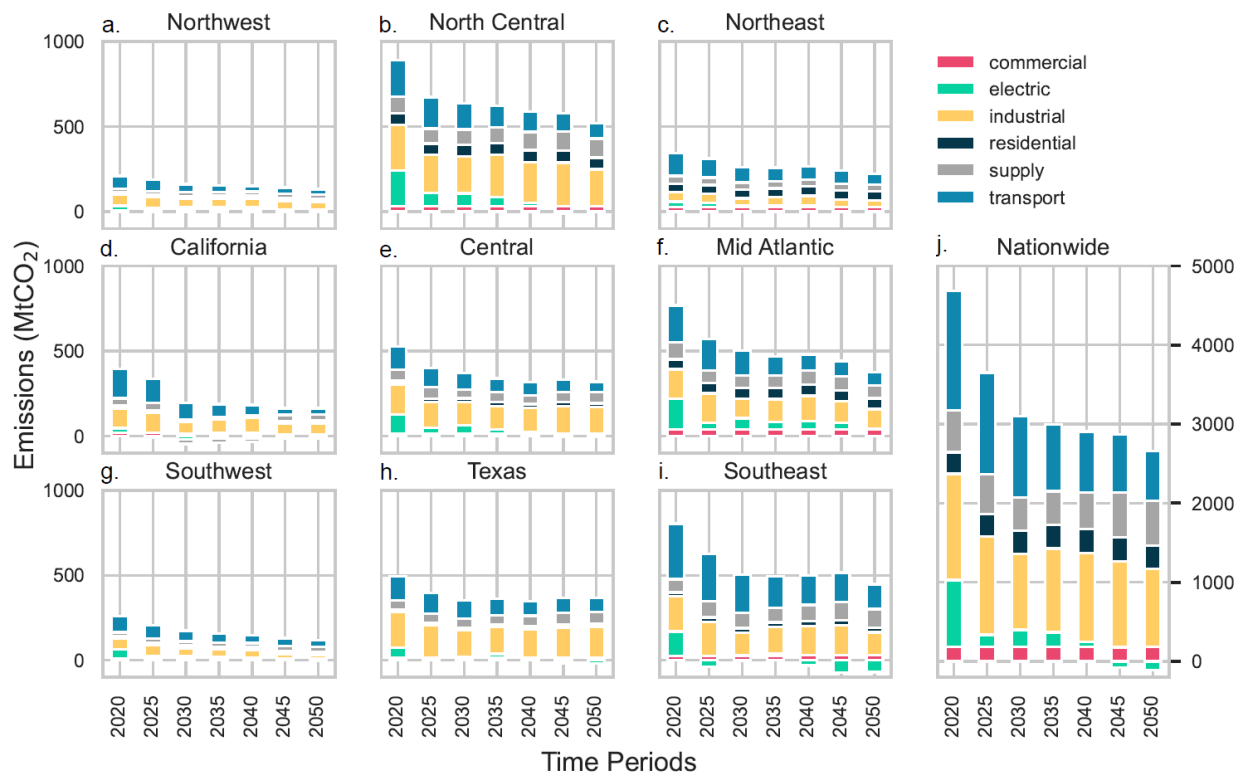
Supplementary Figure 1: Service demands exogenously specified for a) commercial space cooling, b) commercial space heating, c) residential space cooling, d) residential space heating, e) residential water heating, f) compact light duty vehicles (LDV), g) large sport utility vehicles (SUV) LDV, h) pickup LDV and i) small SUV LDVs. These represent 9 of more than 70 demands exogenously enlisted in the database. Demands for the commercial and residential sectors are adopted from National Renewable Energy Lab's (NREL) Electrification Futures Study (EFS). Demands in the transportation sector are extracted from NREL EFS and U.S. Environmental Protection Agency's nine-region market allocation database (MARKAL).

Supplementary Note 1: Emissions – Absolute & Relative Results

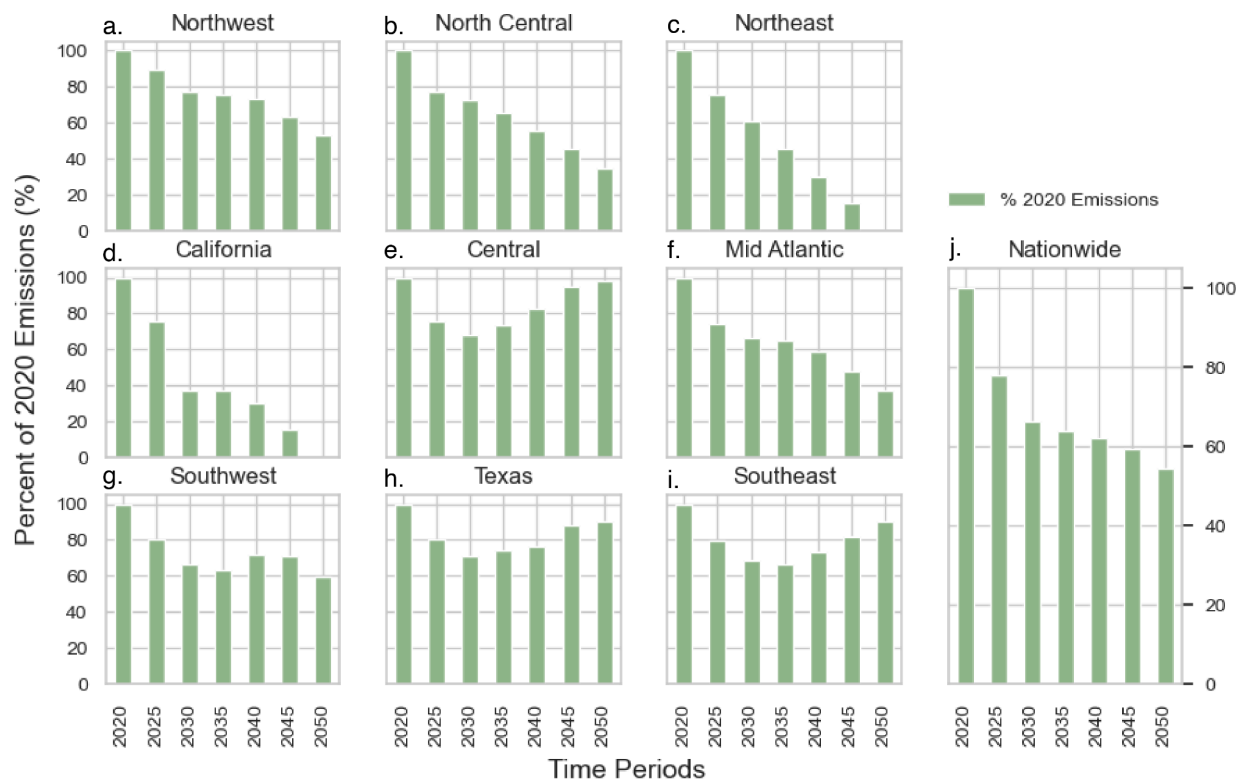
This section provides the absolute, by-region, and by-sector emissions results for both the State and National Action scenarios. Also included are the by-region emissions as a percentage of 2020 emissions for both the State and National Action scenarios. These figures provide a more comprehensive perspective of scenario outputs than just a comparison by difference.



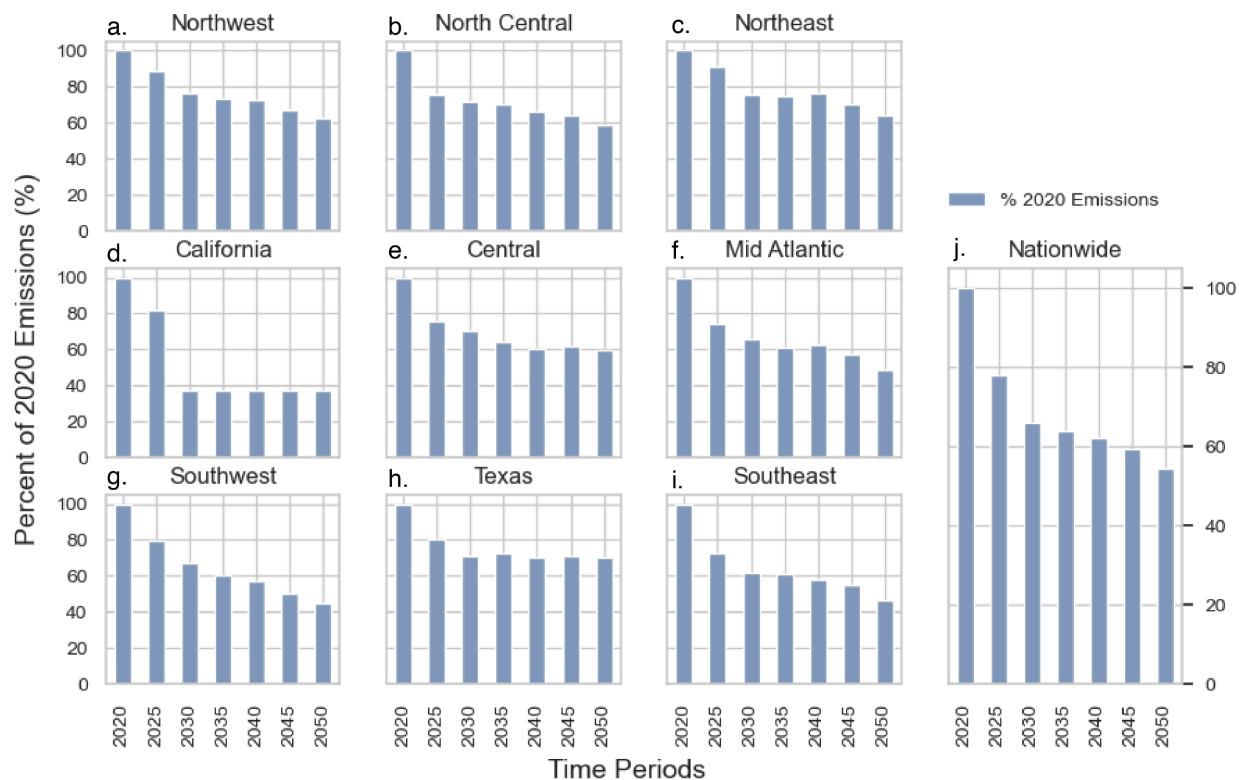
Supplementary Figure 2: Emissions by sector & region for the State Action Scenario. Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. Regions comprised of net-zero participating states such as the Northeast and California result in substantial emissions reductions. Regions with low participation such as the Southeast and Central regions see an increase in emissions in later years.



Supplementary Figure 3: Emissions by sector & region for the National 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. Reductions in emissions are achieved broadly across the regions.



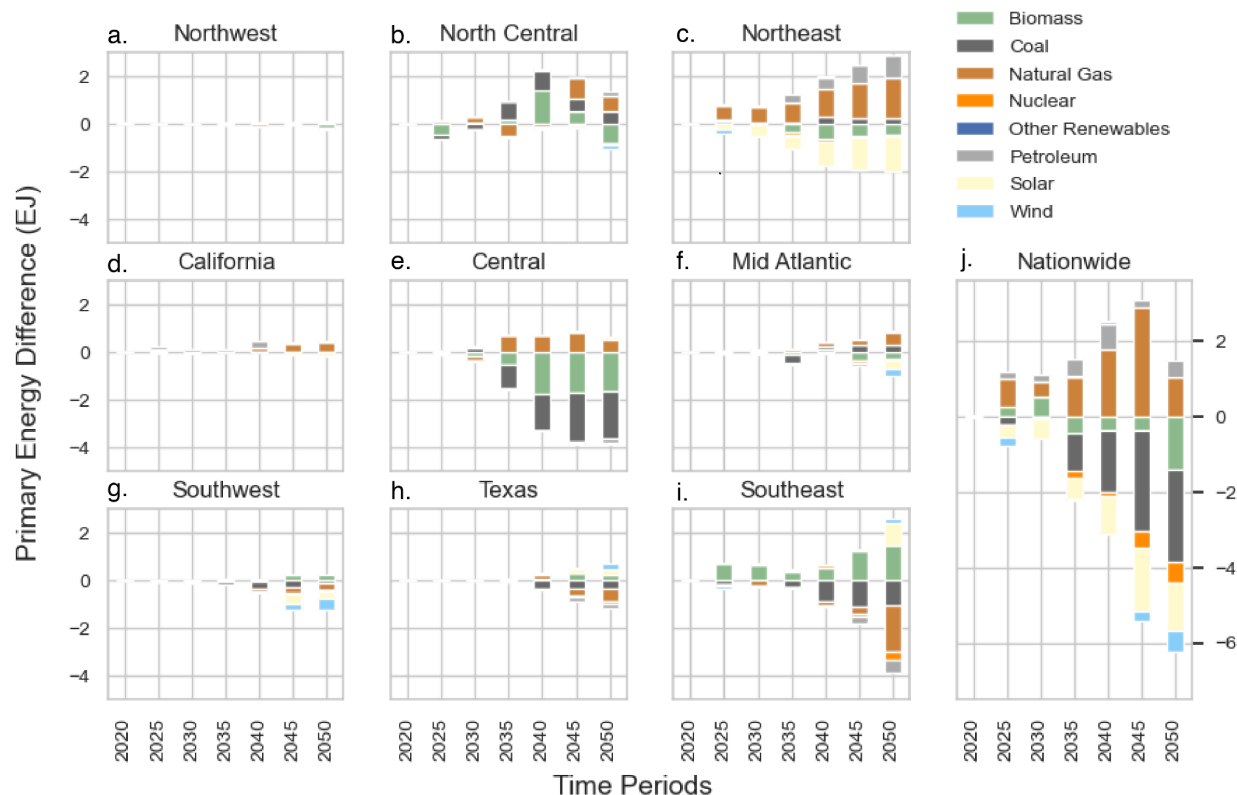
Supplementary Figure 4: Reductions as a share of 2020 emissions, State Action Scenario. Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. The share of emissions reductions varies based on the extent of state participation in net-zero policies.



Supplementary Figure 5: Reductions as a share of 2020 emissions, National 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. Emissions reductions are experienced broadly across regions.

Supplementary Note 2: Primary Energy Use

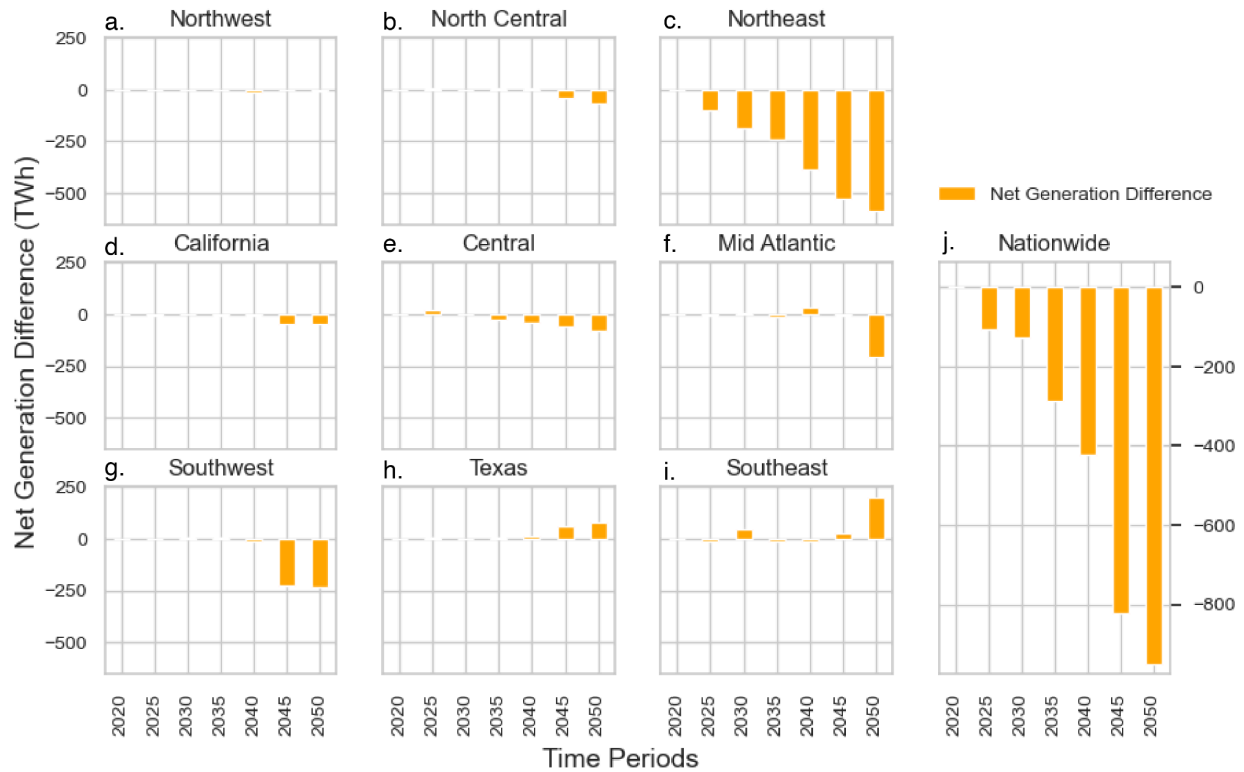
Here, we provide the primary energy consumption across all sectors by fuel type on a by-region basis. Like most figures presented within this paper, this is a comparison through differences. Negative values represent increased use in the State Action scenario, and positive values represent increased National Action scenario use.



Supplementary Figure 6: Primary energy difference by fuel. 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. 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.

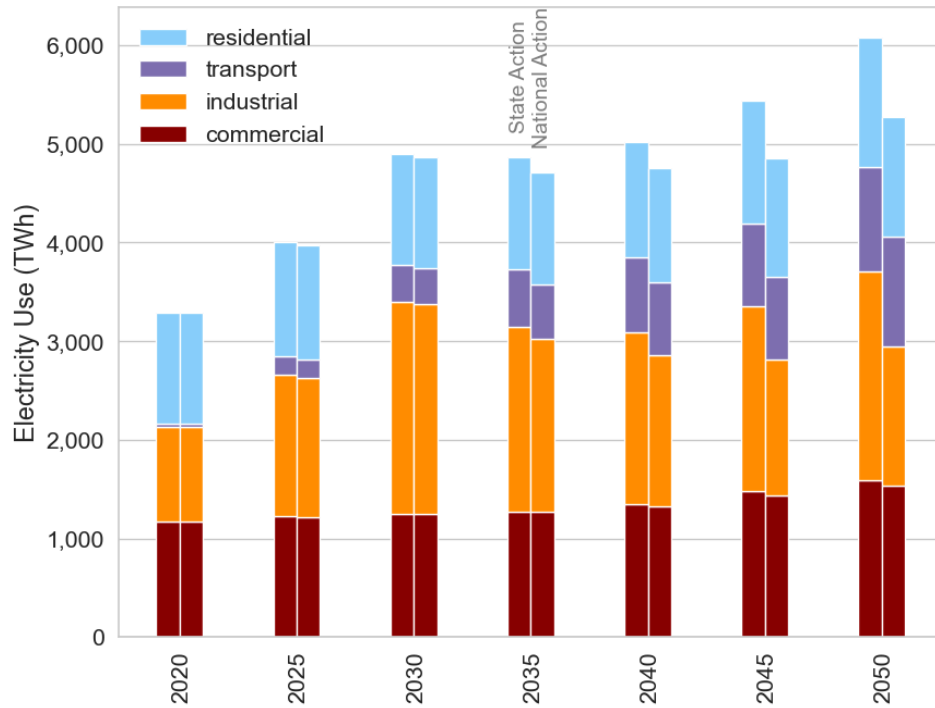
Supplementary Note 3: Electricity Demand

This section provides the net generation difference between the State and National Action scenarios. The by-sector electricity consumption is also provided at the national level.



Supplementary Figure 7: Net generation difference by region. Positive values indicate higher generation in the National Action scenario, while negative values indicate higher generation in the State Action scenario.

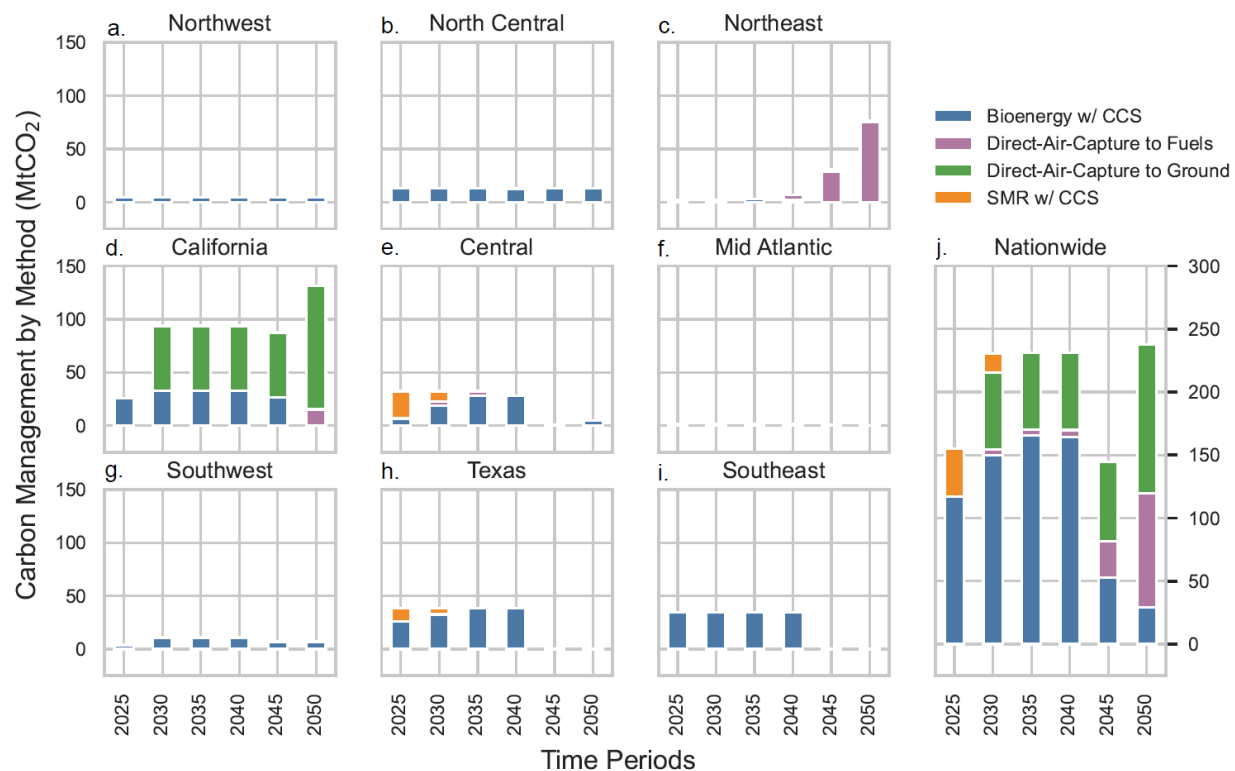
Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. Most regions and the nation as a whole has more electricity generation under the State Action scenario.



Supplementary Figure 8: Electricity consumption by sector, State and National Action scenarios. The State Action scenario has greater overall electricity consumption.

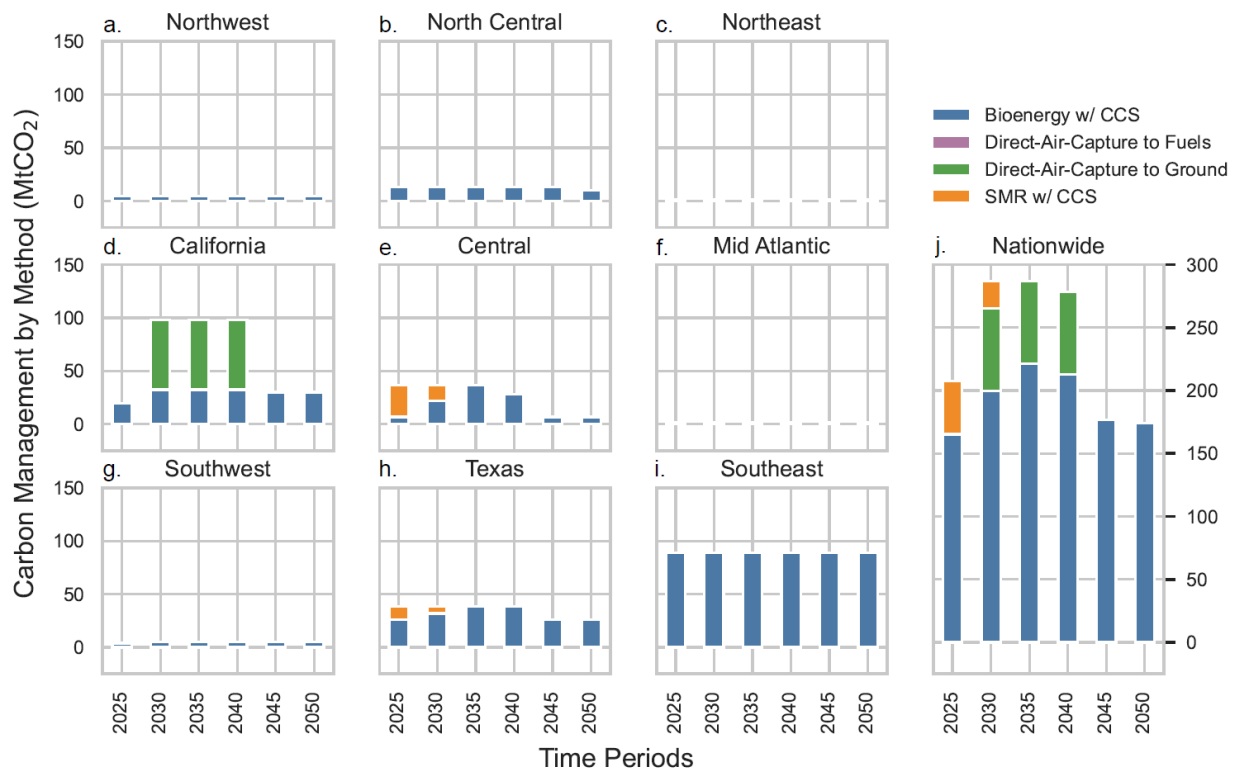
Supplementary Note 4: Carbon Management

This section presents the absolute quantities of carbon management in both the State and National Action scenarios.



Supplementary Figure 9: Carbon management by technology & region for the State Action scenario.

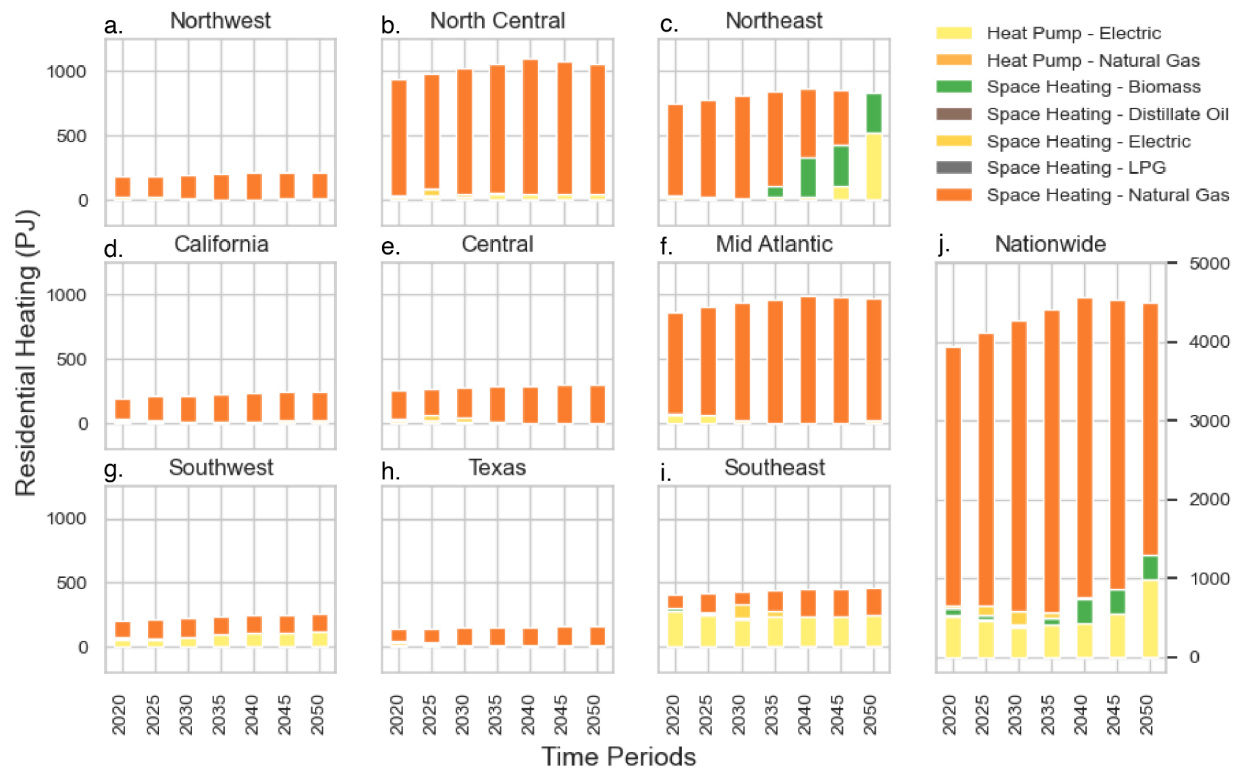
Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. CCS = Carbon capture & sequestration, SMR = Steam methane reformation. Under the State Action scenario, most regions engage in some carbon management.



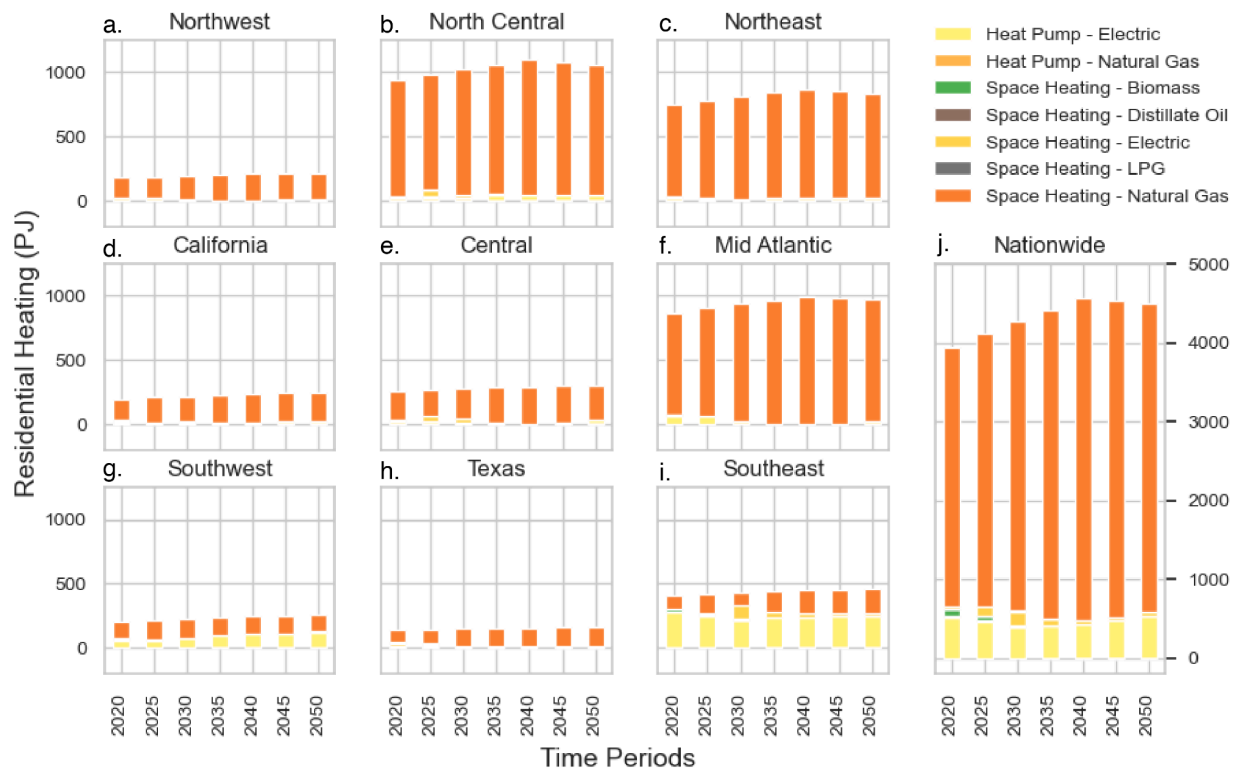
Supplementary Figure 10: Carbon management by technology & region for the National Action scenario. CCS = Carbon capture & sequestration, SMR = Steam methane reformation. Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. CCS = Carbon capture & sequestration, SMR = Steam methane reformation. Under the National Action scenario, more bioenergy is pursued.

Supplementary Note 5: Buildings

This section includes the absolute residential sector heating demand by end-use technology on a regional basis. The absolute amounts for the State and National Action scenarios are included.



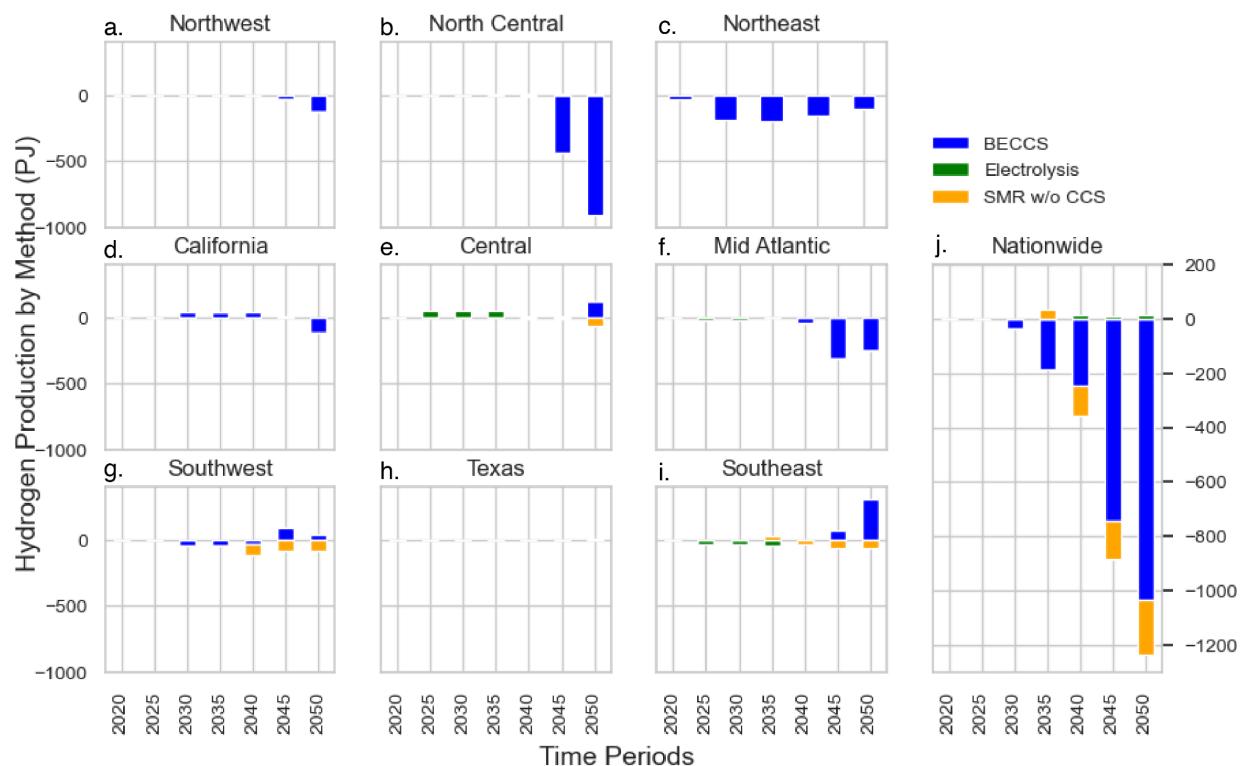
Supplementary Figure 11: Residential sector heating by technology & region for the State action Scenario. LPG = Liquefied petroleum gas. Regions: (a) Northwest, (b) North Central, (c) Northeast, (d) California, (e) Central, (f) Mid-Atlantic, (g) Southwest, (h) Texas, (i) Southeast; and (j) Nationwide results. Under the State Action scenario, the Northeast pursues greater space heating electrification and biomass use.



Supplementary Figure 12: Residential Sector Heating by Technology & Region for the National Action Scenario. LPG = Liquefied petroleum gas. Under the National Action scenario, the energy sources for space heating do not change substantially.

Supplementary Note 6: Hydrogen

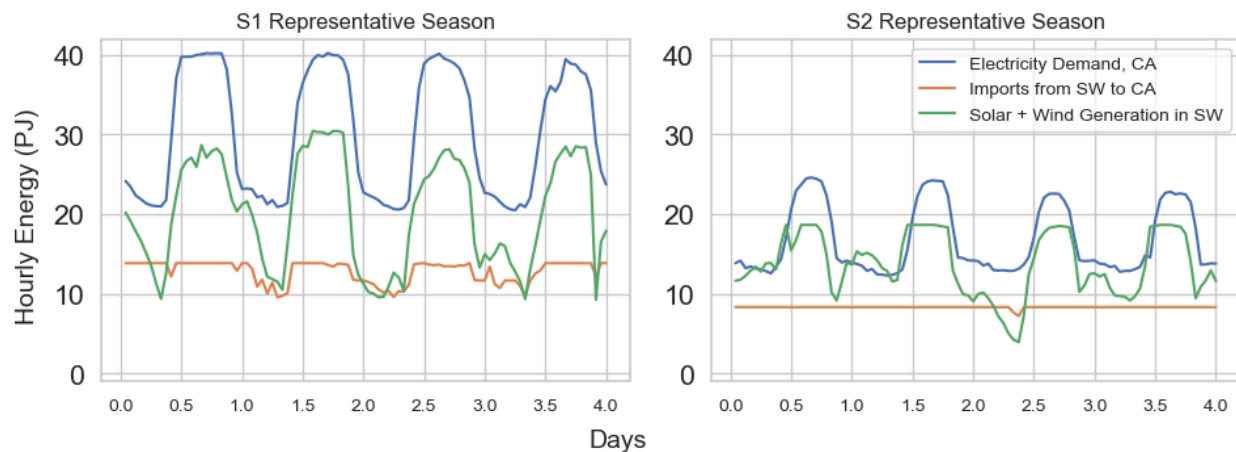
This section provides a by-region difference between the State and National Action scenarios for hydrogen production.



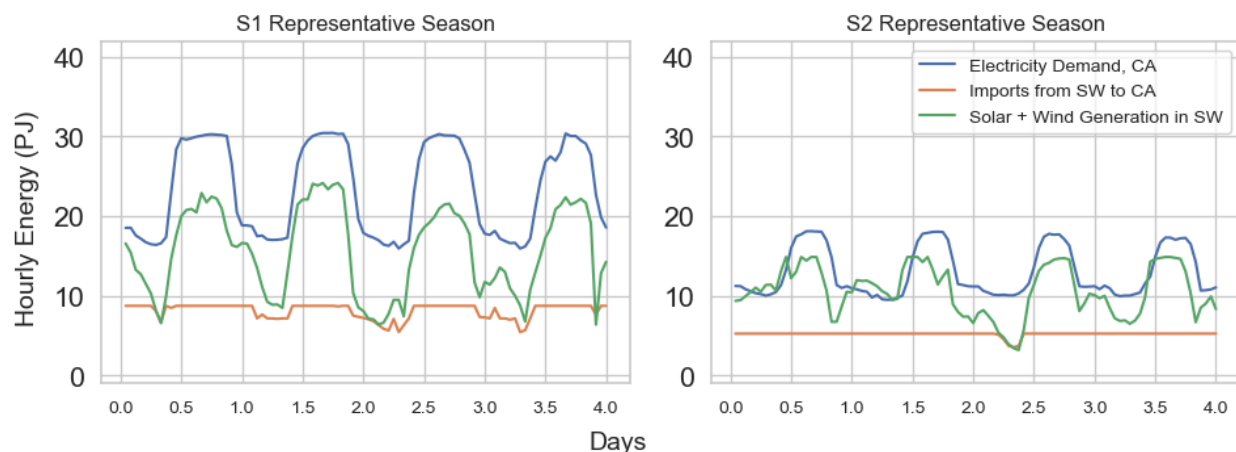
Supplementary Figure 13: Hydrogen production by method. Positive values indicate increased hydrogen production in the National Action scenario, while negative values indicate increased hydrogen production in the State Action Scenario. BECCS = Bioenergy w/ carbon capture & sequestration, SMR = Steam methane reformation, CCS = Carbon capture & sequestration. The State Action scenario results in considerably more BECCS-based hydrogen.

Supplementary Note 7: Inter-regional Trade

This section provides more context as to why we assume Southwestern solar and wind electricity generation is imported into California for the State Action scenario compared to the National Action scenario. In Figure S14, we provide the State Action scenario's electricity demand in California's 2050 model time period compared to Southwestern solar and wind generation, along with the general importing of electricity to California from the Southwest. We cannot isolate the generation source for electricity transmission, but the pattern of imported electricity tracing with Southwestern solar and wind generation can be noted. In Figure S15, which shows the National Action scenario, there is an overall reduction of imported electricity to California from the Southwest and a reduced production of solar and wind-based electricity in the Southwest.



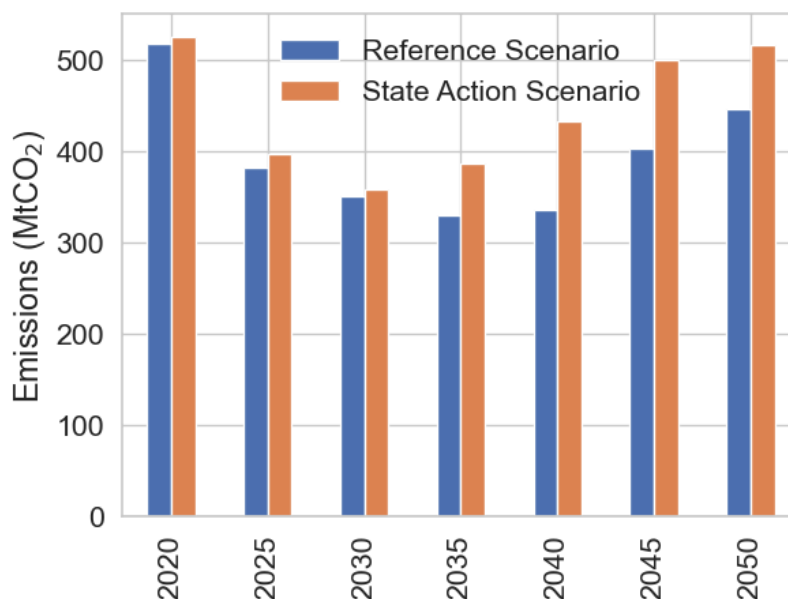
Supplementary Figure 14: California 2050 representative days, State Action scenario. California demand is met, in part, by imports from the Southwest region, which has considerable renewable generation.



Supplementary Figure 15: California 2050 representative days, National Action scenario. Under National Action, California's total electricity demand is lower, with lower imports from the Southwest and lower renewable generation in that region.

Regarding the other form of inter-regional trading, we examine the potential impacts of the Central to North Central region leakage issue by comparing the Central region's State Action scenario emissions with an alternative "No New Policy" (NNP) scenario. This alternative scenario was run within Temoa and used in alternative studies. Emissions comparisons are in Figure S15. This NNP scenario includes the Inflation Reduction Act but places no emissions constraints on regions. We see the State Action scenario induces emissions compared to an apolitical

baseline scenario, indicating the State Action scenario formulation induces true emissions leakage, where the North Central's demands are being met by the Central region and consequently increase the Central region's emissions. The percent increase in State Action scenario emissions compared to the NNP scenario are provided in Table S2.



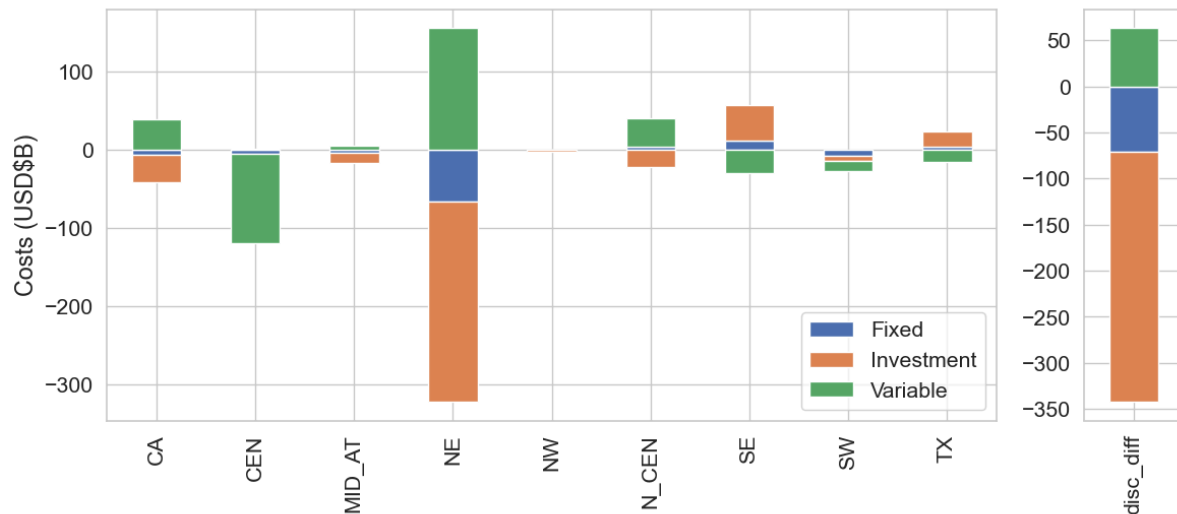
Supplementary Figure 16: Central region emissions in the State Action scenario compared to the Open Energy Outlook Reference Case. This shows that the State Action scenario leads to an increase in emissions in the Central region, suggesting regional emissions leakage.

Supplementary Table 2. Central Region State Action Scenario Emissions Versus the Open Energy Outlook Reference Case.

Time Periods	Reference Scenario Emissions (MtCO ₂)	State Action Scenario Emissions (MtCO ₂)	State Action Scenario Emissions Increase (% of Reference)
2020	518.58	525.50	1.3%
2025	382.10	396.96	3.9%
2030	350.86	358.01	2.0%
2035	330.54	387.40	17.2%
2040	336.41	433.45	28.8%
2045	403.28	499.85	23.9%
2050	446.25	516.99	15.9%

Supplementary Note 8: System Cost Results

Provided in this section is a more detailed cost breakdown of each scenario. Presented in Figure S16 is the by-region cost difference between the State and National Action scenarios, segmented by fixed, investment, and variable costs. Identical to the figures presented within the ordinary paper, negative values represent increased costs in the State Action scenario relative to the National Action scenario. In contrast, positive values represent increased costs in the National Action scenario. Generally, we see an increase in variable costs in regions where they reduce their emissions relative to the other scenario, and increased investment and fixed costs for the scenarios where that region emits more. At the national level, we see the National Action scenario has more variable costs, which are offset by the added investment and fixed costs of the State Action scenario. Tables S3 and S4 provide the cost differences between scenarios.



Supplementary Figure 17: Regional cost differences/ Positive values indicate higher costs in the National Action scenario, while negative values indicate higher costs in the State Action scenario. The largest cost differences are shown in the Northeast region.

Supplementary Table 3: Discounted Fixed, Investment and Variable Costs

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

Supplementary Table 4: Raw and Relative Discounted Investment Differences, by Region

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

Supplementary References

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