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Supplementary information

The surprisingly inexpensive cost of state-driven emission control strategies

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Supplementary Information for "The Surprisingly Inexpensive Cost of State-Driven Emission Control Strategies"

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Supplementary Note 1: Literature review on public opinion and climate policy

Climate change has become an intensely polarizing issue in American politics over recent decades.[1] Public opinion on climate change policy reflects this reality. For example, in April 2019, 81% of Democrats said they think that global warming should be a high or very high priority for the president and Congress, versus 16% of Republicans and 47% of Independents.[2] Specific climate policies, however, vary in the degree to which they promote polarizing attitudes. Funding more research into renewable energy, for example, was supported by 84% of Americans nationally, including 94% of Democrats and 77% of Republicans in 2017.[3] Support for regulating CO_2 as a pollutant, in contrast, showed strong political and geographic differences. In 2016, the percentage of Democrats who supported regulating CO_2 as a pollutant was 84% compared with 61% of Republicans.[4] Republicans in the west were less supportive than those in the northeast, while Democrats in the southeast were less supportive on average than those elsewhere.

In general, the geography of public opinion on climate change largely reflects the geography of climate policy. State governments in particular play an important role in setting US climate policy. California and a regional cooperative comprised of nine northeastern states are already operating cap-and-trade systems for example, and at least ten states have introduced carbon fee or tax proposals. States also set renewable portfolio standards (RPS) – policies that require electricity suppliers to obtain a specific portion of their electricity from renewable resources.

The trend in recent years has accelerated climate policy polarization. Democrats have dramatically increased their support for action on climate whereas Republicans' support has remained relatively unchanged. Independents increased their support gradually, moving towards positions similar to many Democrats.[2] Such changes are reflected in state-level estimates of public support for climate policy.[4] A recent surge in Democratic support for political action on climate change has reached an all-time high. When asked about global warming as a voting priority, liberal Democrats rank the issue third out of 29, while "environmental protection" more broadly ranks second (healthcare takes first place). In contrast, global warming ranks 29 out of 29 as a voting issue for conservative Republicans.

For environmental public opinion generally, partisan politics is now stronger than geographic differences.[5] That is, the difference between Democrats' and Republicans' support for environmental policy is larger than it is between states. Fundamentally, this partisan divide in American politics reflects different values, which have been shown to influence policy preferences more strongly than party affiliation or ideology.[6] Those with pro-egalitarian values (i.e., concerned with injustice in the distribution of wealth) in particular tend to support climate

policy, while those with stronger individualistic values (i.e., concerned with restrictions on individual autonomy, particularly via government regulation) show less support. As a result, the economics of climate policy may prove to be of greater concern to many Americans (i.e., those with individualistic values) than issues surrounding the injustice of climate impacts.

Regardless of any causal role that the public may play in driving climate policy, our *Heterogeneous* scenarios require only that public support is positively correlated with policy enactment at the state level. We also test the sensitivity of this relationship by assuming alternative shapes and by using a different survey question (see more in Figure 6, Supplementary Methods, and Extended Data Fig. 5).

Supplementary Note 2: Comparison with America's Pledge study

Here, we compare our scenarios with the America's Pledge (AP) study.[7] Focusing on the 2025-2030 time horizon, the AP study examined the impacts of climate action by states, cities and businesses across the United States on the abatement of greenhouse gas emissions. By simulating various policy instruments that have been proposed by each state, the AP study complements our approach that focuses only on the level of policy stringency.

The AP study includes three scenarios: Current Measures, Climate Action Strategies, and Enhanced Engagement. Since the AP study only modeled until 2030, we restrict to this time frame when comparing our simulations to theirs. As shown in the figure below, by 2025/2030, the total energy-system CO_2 emissions in the three AP scenarios are in between our 40% and 60% decarbonization scenarios.

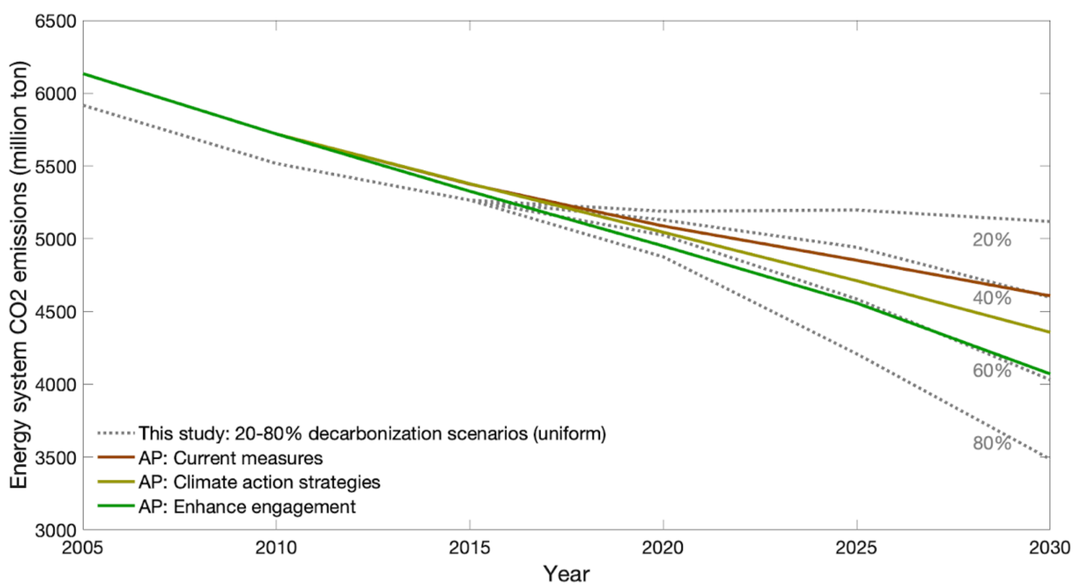


Figure. National total energy system CO_2 emissions in our scenarios and in the America's Pledge study.

We further compare the sectoral CO_2 emissions in the AP study and ours (see the figure below). We find in both studies, the largest CO_2 reduction by 2030 occurs in the electricity sector. Compared to our analysis, the AP scenarios project more CO_2 reduction in the transport sector, even in the Current Measures (CM) scenario. Their Enhanced Engagement (EE) scenario also predicts more reduction in the building sector. In addition, the AP scenarios project a net increase in industrial CO_2 emissions relative to 2015 across all three scenarios, whereas our 60% decarbonization scenarios project near-zero changes in industrial CO_2.

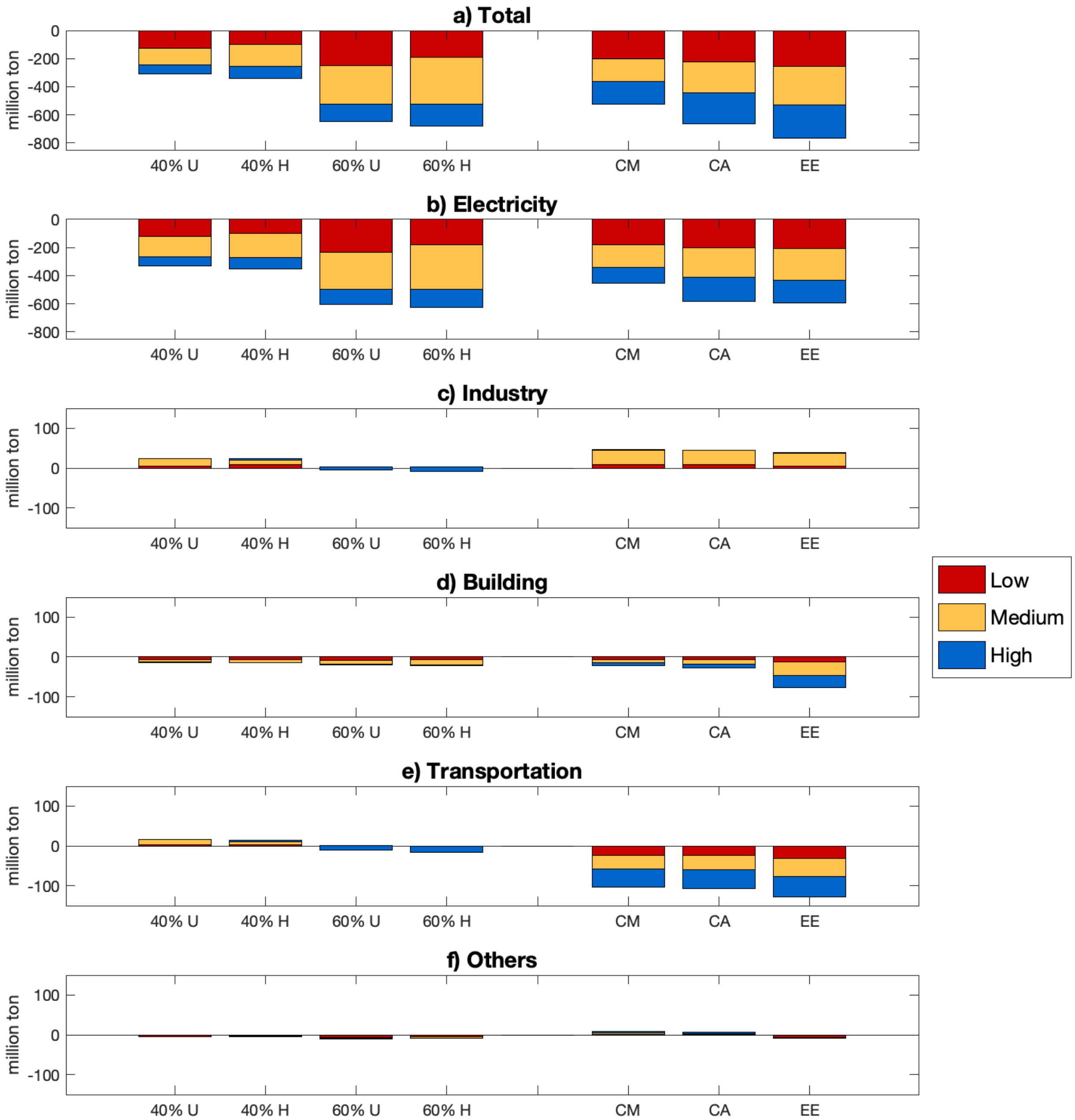


Figure. Changes in sectoral CO_2 emissions in 2025 relative to 2015. *40% U, 40% H, 60% U, and 60% H scenarios are from our study. CM, CA, and EE are from the AP study. 40% U: 40% decarbonization with the uniform approach. 40% H: 40% decarbonization with the heterogeneous approach. 60% U: 60% decarbonization with the uniform approach. 60% U: 60% decarbonization with heterogeneous MAC. CM: Current Measures. CA: Climate Action Strategies. EE: Enhanced Engagement. Low, Medium, and High represent states with a low, medium, and high support rate for climate policy, respectively.*

Supplementary Note 3: Sensitivity analysis on key technology assumptions

In support of Figure 6 in the main text, here we delve into the technology details to compare the three technology-related sensitivity analyses.

First, the total primary energy use at the national level is reduced under all three technology constraints (see the figure below). The reduction is the largest in No CCS scenarios. This is because without CCS, fossil energy uses, including coal, natural gas, and oil, are reduced substantially in a carbon-constrained world.

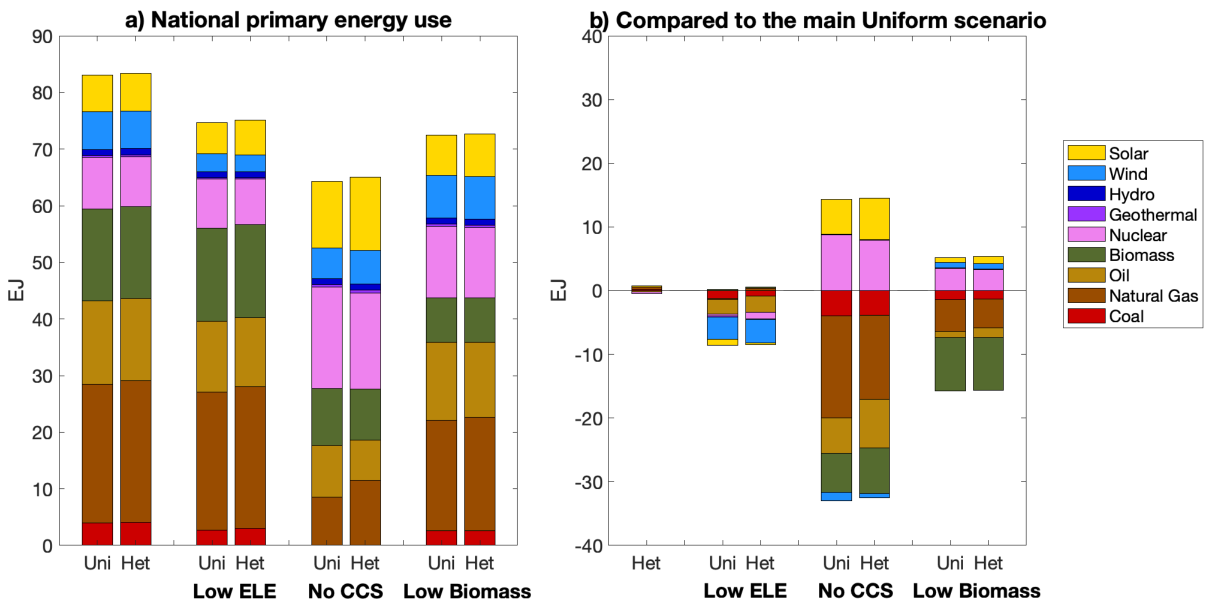


Figure. National primary energy use by fuel in 2050 to achieve 80% decarbonization. *Panel a) shows the national primary energy use in the main scenarios (left two bars), as well as under low electricity infrastructure investment (Low ELE), no CCS, and low biomass availability. Panel b) shows the difference in each scenario to the main, uniform case. In both panels, "Uni" and "Het" represent the uniform and heterogeneous approach, respectively.*

At the same time, the national final energy use is also reduced under the three technology constraints, reflecting a shift towards energy efficient measures to achieve decarbonization when some mitigation technologies are constrained (see the figure below). Comparing to the main scenario with a uniform approach, in the Low ELE scenarios, the uses of electricity and refined liquids are reduced, while natural gas (mostly with CCS) and hydrogen uses are increased. In comparison, in the No CCS and Low Biomass scenarios, the uses of natural gas and refined liquids are reduced, along with an increase in hydrogen use. Since the technology costs associated with the options using natural gas and refined liquids are often lower, the shift away

from these fuels in No CCS and Low Biomass scenarios results in higher costs than in Low ELE scenarios.

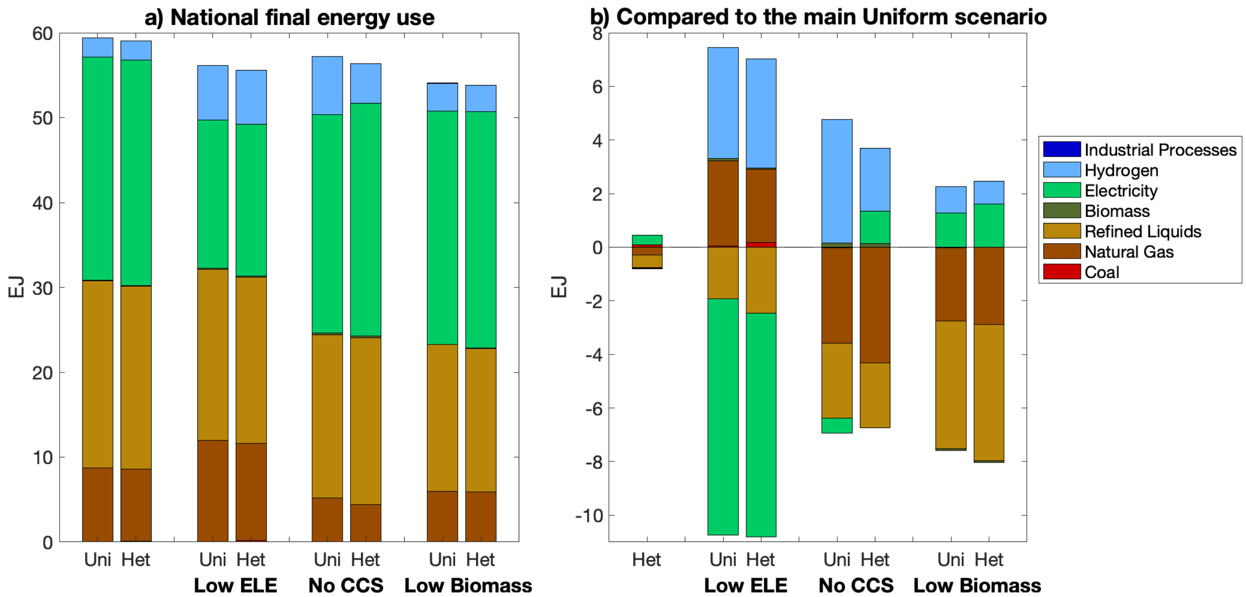


Figure. National final energy use by fuel in 2050 to achieve 80% decarbonization. *Panel a) shows the national final energy use in the main scenarios (left two bars), as well as under low electricity infrastructure investment (Low ELE), no CCS, and low biomass availability. Panel b) shows the difference in each scenario to the main, uniform case. In both panels, "Uni" and "Het" represent the uniform and heterogeneous approach, respectively.*

Finally, the three technology constraints also lead to different patterns in electricity trade as well as the state-level patterns in BECCS deployment and associated CO_2 sequestration (see the figure below for the results to achieve 80% decarbonization). Among the three technology constraints, the Low ELE scenarios show the smallest difference in cross-grid electricity trade between the uniform and heterogeneous approach, but the largest difference in state-level pattern of CO_2 sequestration by BECCS. This is because with limited electricity infrastructure, electricity trade is also hindered, making flexibility in bioliquids production location the most important mechanism to take advantage of the cross-state variations in the marginal abatement costs (MACs). In comparison, the No CCS scenarios are associated with significant differences in electricity trade between the uniform and heterogeneous approach. This is because without CCS, bioliquids production with CCS is also unavailable (i.e., zero CO_2 sequestration from BECCS), making electricity trade the most important mechanism to take

advantage of the cross-state variations in MACs. The electricity trade and BECCS patterns in Low Biomass scenarios are in between the Low ELE and No CCS scenarios.

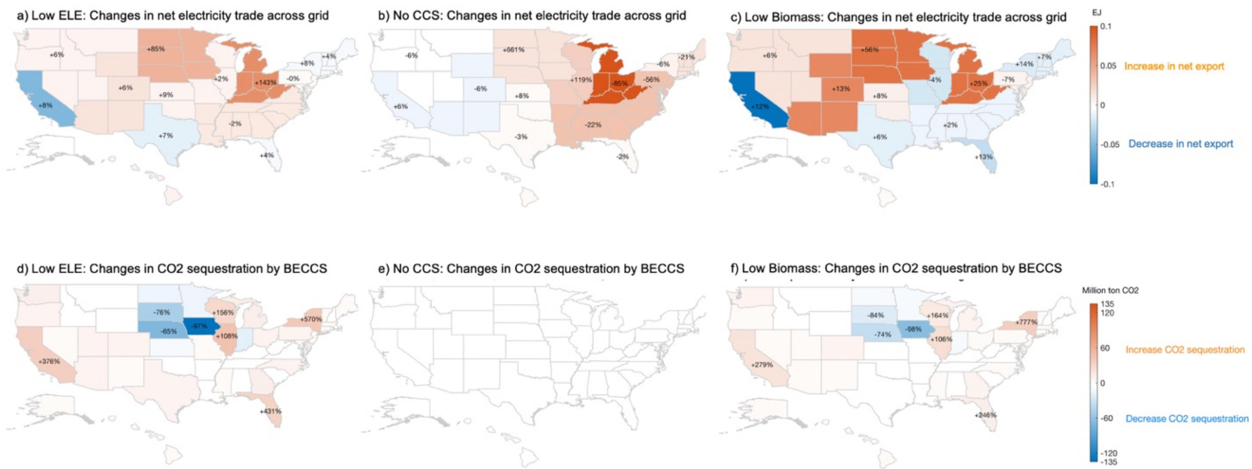


Figure. Changes in the Heterogeneous approach compared to the Uniform approach to achieve 80% decarbonization (i.e., "80% Uniform" scenario). *Panel a-c) show the changes in net electricity trade for 15 electricity grid regions. The background colors represent the absolute changes in net electricity export (i.e., generation minus demand). The black numbers show the percent differences: the positive numbers indicate that a net exporting (importing) grid in "80% Uniform" further increases its export (import), while the negative numbers indicate that a net exporting (importing) grid in "80% Uniform" reduces its export (import). Panel d-e) show the changes in CO_2 sequestration by BECCS. The background colors represent the absolute differences in CO_2 sequestration, and the black numbers indicate the percent differences in selected states. Panel a) and d) show the results with low electricity infrastructure. Panel b) and e) show the results with no CCS. Panel c) and f) show the results with low biomass availability.*

Supplementary Note 4: Literature review on heterogeneous action across countries

At the global scale, several studies[8–11] have looked at the cost of delaying policy action—for example, the adoption of only policies through 2020 or 2030, with variations in stringency across countries, before converging on a homogeneous, globally-coordinated policy regime to achieve a long-term climate target such as limiting warming 2 degrees above pre-industrial levels. Such work generally shows that transient heterogeneity raises costs about 20% compared with first-best strategies where all countries embark on stringent and coordinated policies immediately.

Other studies that explore more profound heterogeneities generally find costs are higher. In a large inter-model comparison exercise of scenarios in which developing countries join a coordinated global climate policy regime only after 2030,[12] the effects of heterogeneity yield a doubling of costs, and some model configurations found it impossible to meet environmental goals because of large emissions from less regulated global emitters; other studies have found similar costly results.[13]

Some research has looked at particular factors that could explain highly heterogeneous policy responses. In addition to variation in political interests, there are variations in the quality of government and market institutions that affect the cost of investment capital, perceptions of risk, and the time horizons for investment planning,[14] with one study finding real-world variations in costs of capital alone yielding a 40% rise in global mitigation costs, when compared with standard assumptions that investment risks and capital costs are homogeneous.[15]

Looking across the totality of the literature, in 2014 the IPCC assessed that inter-country heterogeneity in technology and policy assumptions could be a substantial cause of increased social cost of emission policy, with a large number of scenarios suggesting cost increases over 40%.[16]

Supplementary Methods

1. Main scenarios

For the main *Heterogeneous* scenarios, we assume state-level marginal abatement cost (or carbon price) increases non-linearly with the public support level. The mathematical function is:

$$\frac{MAC_s}{MAC_{Support=50\%}} = \sqrt[3]{\frac{Support_s - 50}{50}} + 1$$

where MAC_s and $MAC_{Support=50\%}$ are the marginal abatement cost in State s and a hypothetical case where the public support level is 50%, respectively; $Support_s$ represents the public support level in State s (in percentage). We then calculate the ratio of the MAC in each state to the MAC in Washington DC (support rate of 66.7%) as shown in Figure 1b and Figure 2 in the main text. Using this method, the ratio of the highest to the lowest state-level MAC is 3.27.

2. Alternative formations of policy heterogeneity based on public support level

We design a series of alternative heterogeneous approaches that are also based on the public opinion survey results from the Yale Program on Climate Change Communication,[17] but constructed using different assumptions.

1) Heterogeneous (Gov)

Here we use the results from a different question from the same survey, i.e., “Do you think your *governor* should do more to address global warming?”, but still assume the state-level MAC increases non-linearly with the public support level as in our main *Heterogeneous* approach. Comparing the responses to the “governor” question to those to the “local official” question, the overall public support level remains consistent in most states. The differences are larger in a few states, such as UT, AK, and SD (see the figure below).

Note that we decide to use the “local officials” question for our main scenarios, because this question reveals better the sentiments about “doing more” against a baseline that is generally low. By contrast, the “governor” question could be less representative of the willingness-to-act, because it can be viewed as a referendum on whether the state was doing enough based on the information in the news, not its absolute level of efforts.

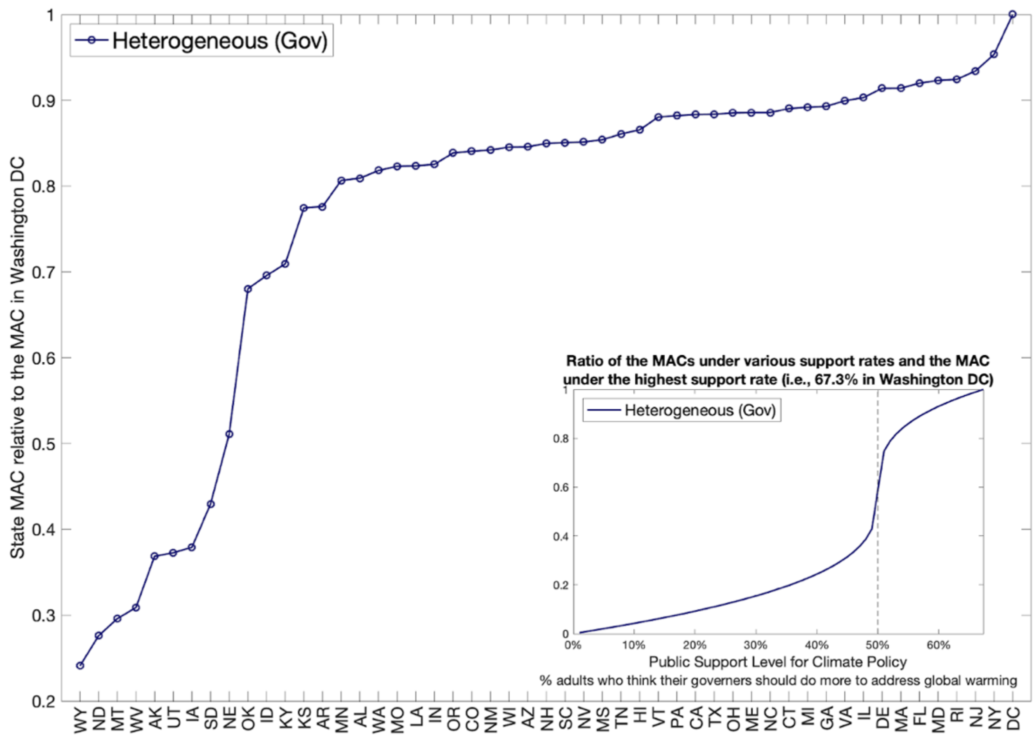


Figure. Heterogeneous (Gov) approach: Ratio of the marginal abatement cost (MAC) in each state and the MAC in Washington D.C. *(the state with the highest public support level)****.*** *Here we use the results from the survey question "Do you think your governor should do more to address global warming" and follow the same method as the main heterogeneous approach to construct state variations in MAC.*

b) Heterogeneous (LN)

Here we use the results from the survey question "Do you think your *local officials* should do more to address global warming?", but assume the state-level MAC increases linearly with the public support level. The mathematical function used under the *Heterogeneous (LN)* approach is: $\frac{MAC_s}{MAC_{DC}} = \frac{Support_s}{Support_{DC}}$, where MAC_s and MAC_{DC} are the marginal abatement costs in State s and in Washington D.C. (where the current public support level is the highest), respectively; $Support_s$ and $Support_{DC}$ are the public support levels in State s and in Washington D.C., respectively. To make the linear and non-linear heterogeneous approaches comparable, we keep the range of state variations the same by setting the relative ratio of the highest (i.e., DC) and the lowest (i.e., WY) MAC the same under the linear and non-linear Heterogeneous approaches.

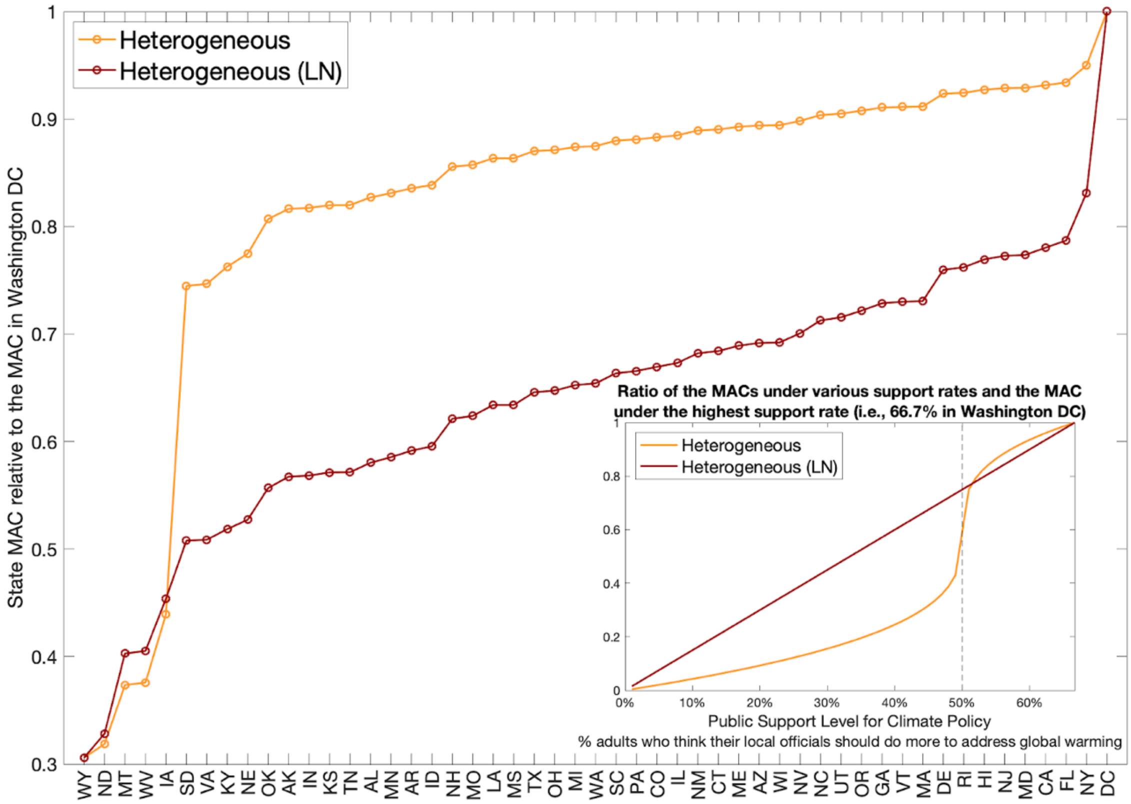


Figure. Ratio of the marginal abatement cost (MAC) in each state and the MAC in Washington D.C. under Heterogeneous and Heterogeneous (LN) approach, respectively. *The inserted figure represents the relationships between support rate and MAC under these two approaches, by showing the ratio of the MAC at any given support rate and the MAC under the highest support rate of 66.7% observed in Washington D.C.*

c) *Heterogeneous (+ range)*

Here we use the results from "local officials" question but increase the range of the cross-state variations for MACs: the ratio of highest MAC to the lowest MAC increases from 3.27 under the main *Heterogeneous* approach to 10 under *Heterogeneous (+range)* approach. The mathematical formula is:

$$\frac{MAC_s}{MAC_{Support=50\%}} = 0.20779 \times \sqrt[3]{\frac{Support_s - 50}{50}} + 0.4688,$$

where MAC_s and $MAC_{Support=50\%}$ are the marginal abatement cost in State s and a hypothetical case where the public support level is 50%, respectively; $Support_s$ represents the public support level in State s (in percentage).

d) *Heterogeneous (3 zero)* and *Heterogeneous (5 zero)*

Here we use the results from the "local officials" question but set zero carbon price in the 3 or 5 states with the lowest support rate.

In summary, the state-level MAC for the main and alternative heterogeneous approaches are shown in the figure below (using 40% decarbonization as an example).

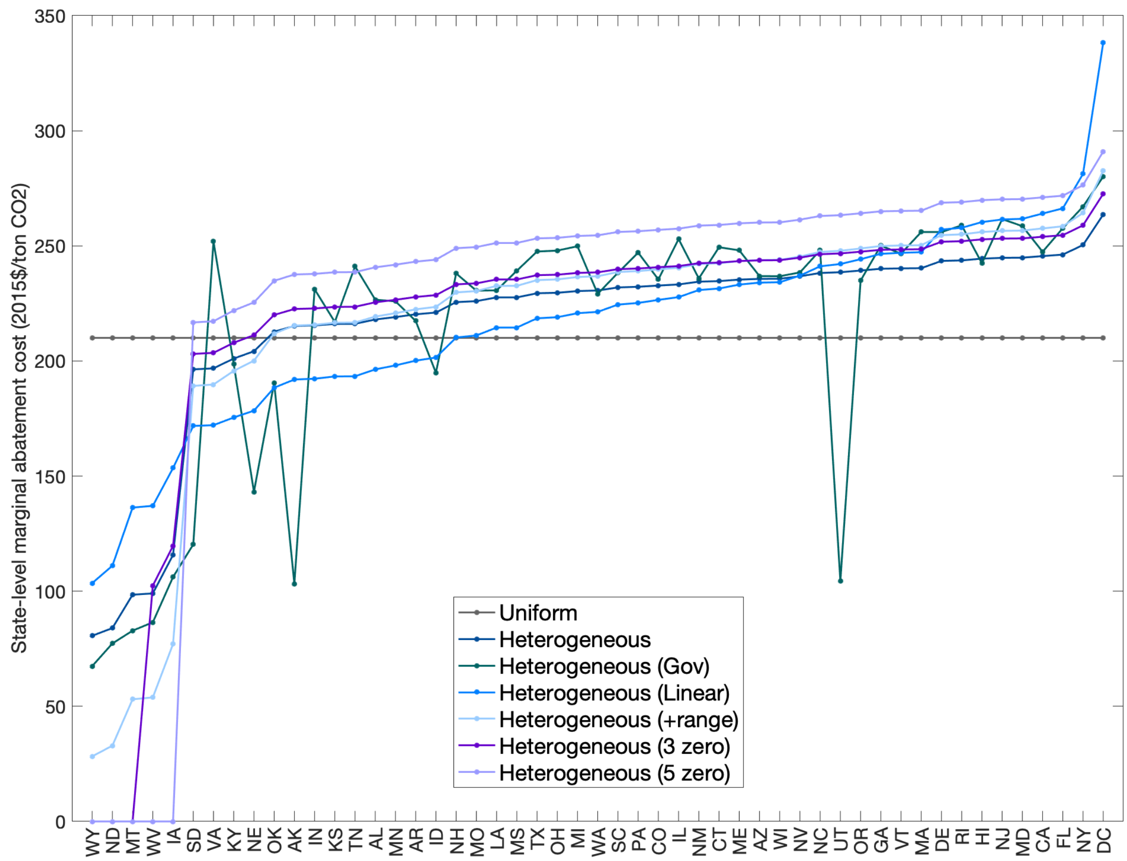


Figure. Model computed state-level marginal cost of carbon mitigation policies to achieve 40% decarbonization under the uniform and different heterogeneous policy approaches.

3. Alternative formations of policy heterogeneity based on the America's Pledge study

We construct an alternative heterogeneous approach in which we vary state-level MACs based on their existing climate commitments derived from the America's Pledge study (see more Supplementary Note 2 above). We assume that the states that are projected to reduce more CO_2 by 2025 (percent wise) in the Current Measures scenario in the AP study will continue to be climate leaders by mid-century. These states are modeled in GCAM-USA to have a higher MAC. Note that our main *Heterogeneous* approach sets higher MACs in states with higher climate

policy support. In comparison, the *Heterogeneous (AP)* approach sets higher MACs in states that are committed to more CO_2 mitigation by 2025 based on the AP study, which is weakly correlated with the current policy support levels.

Specifically, we first calculate the percent changes in energy-related CO_2 from 2025 to 2015 in the Current Measures scenario in the AP study. We then construct the *Heterogeneous (AP)* approach by setting the relative ratios of state MACs in the GCAM model as the relative ratios of the projected percent changes in CO_2 calculated in the first step (see more in the figure below). To make the *Heterogeneous (AP)* approach comparable with our main *Heterogeneous* approach, we assume the range for state variations in MACs to be the same, i.e., the scale factors for the highest and the lowest MAC are set at the same levels in the *Heterogeneous* and *Heterogeneous (AP)* approaches.

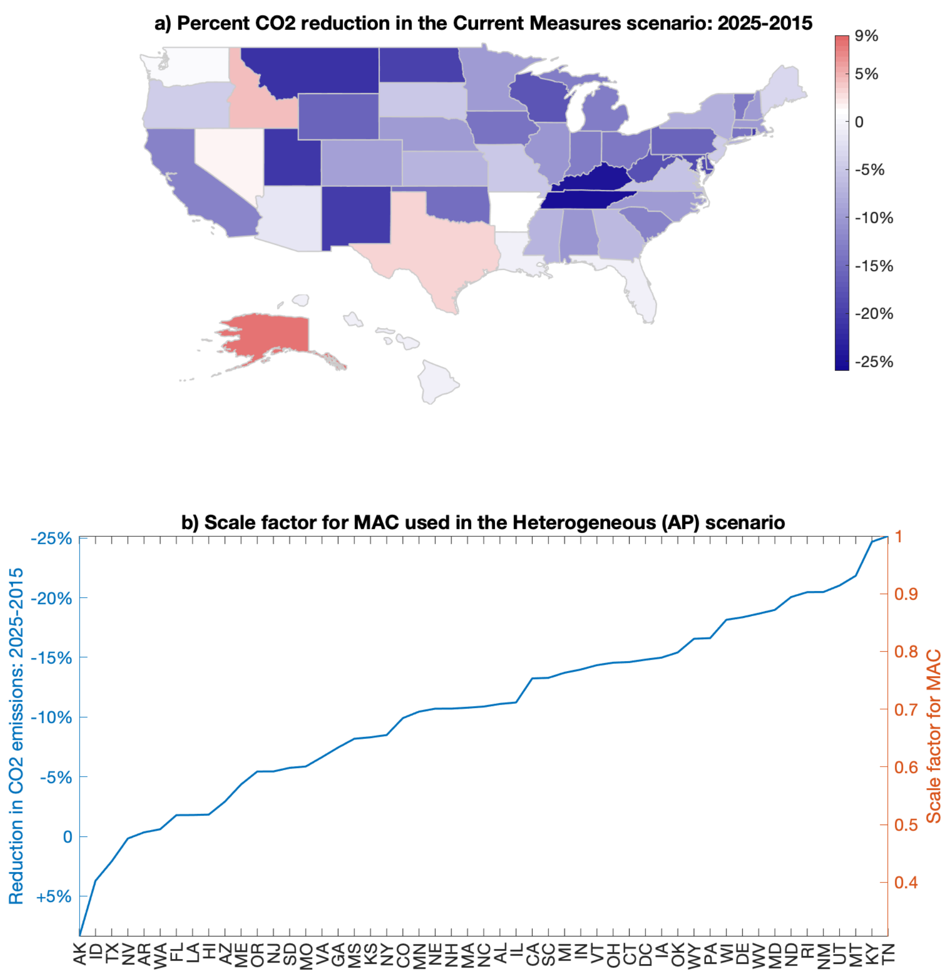
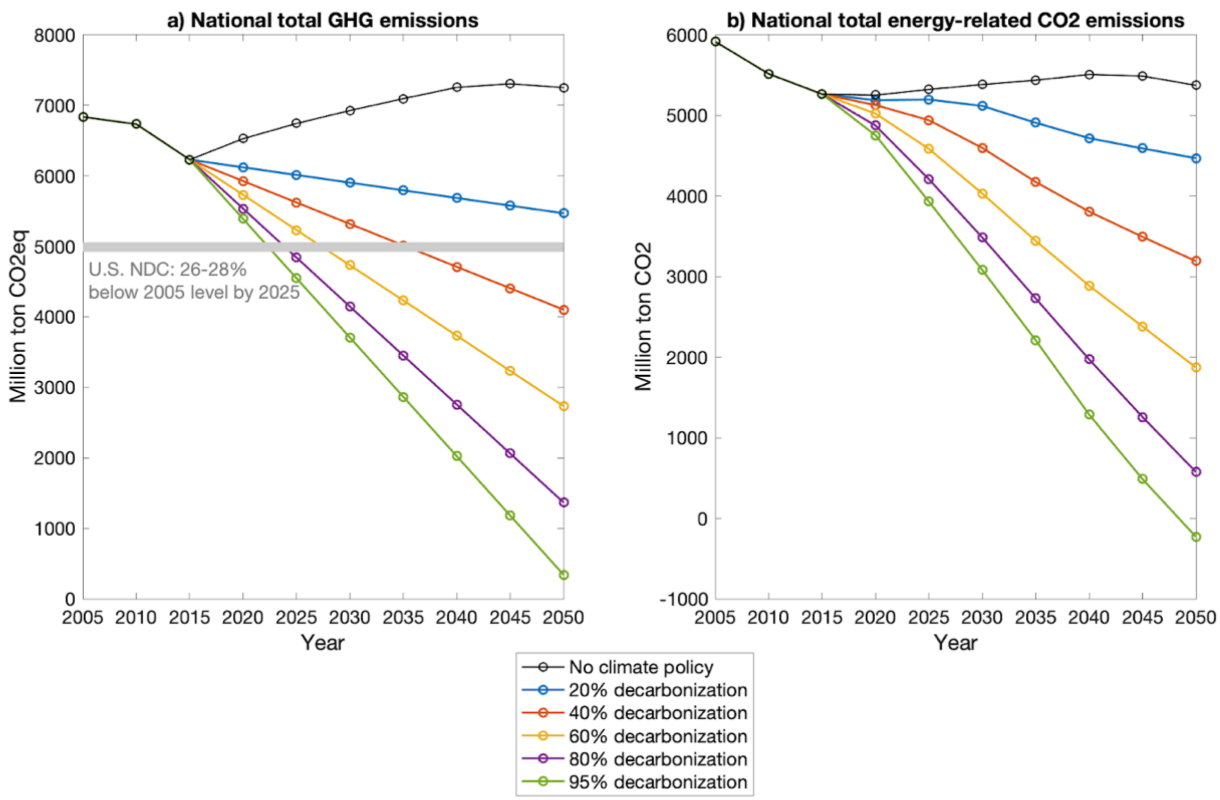
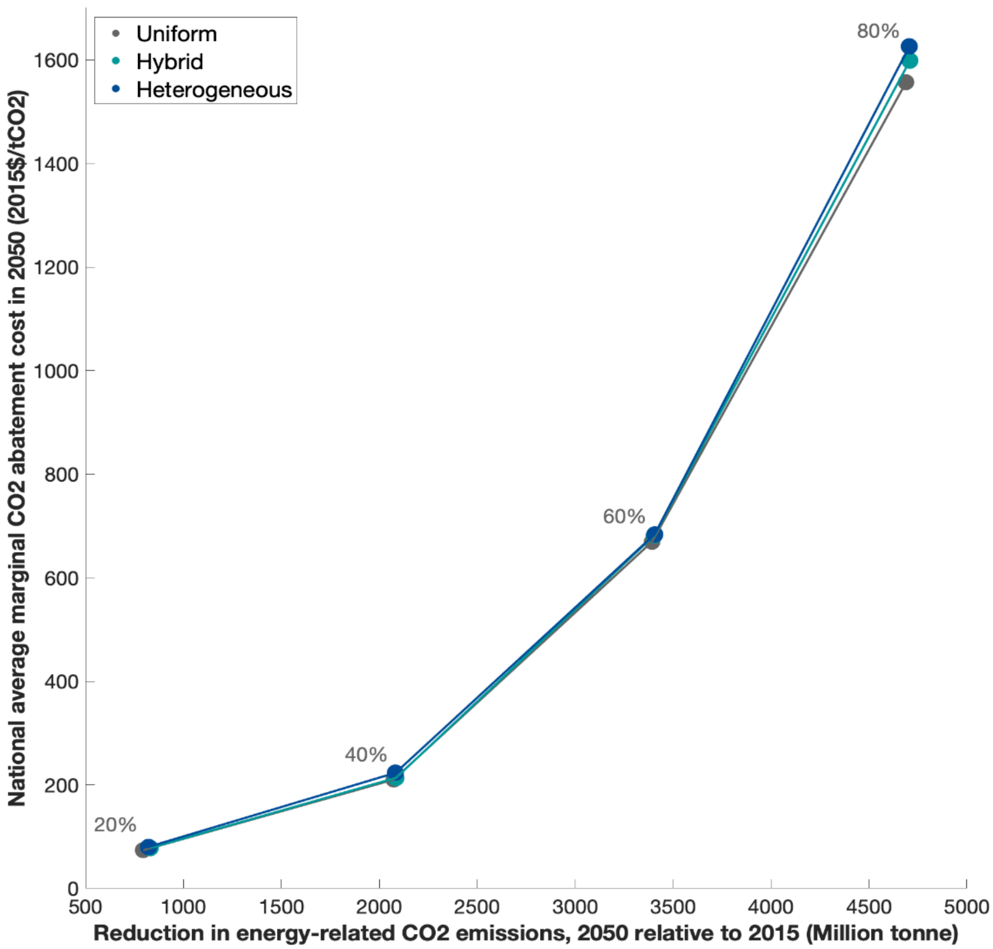


Figure. a) Percent CO_2 reduction (2025 minus 2015) in the Current Measures scenario, and b) the scale factor for MAC utilized to construct the Heterogeneous (AP) approach.

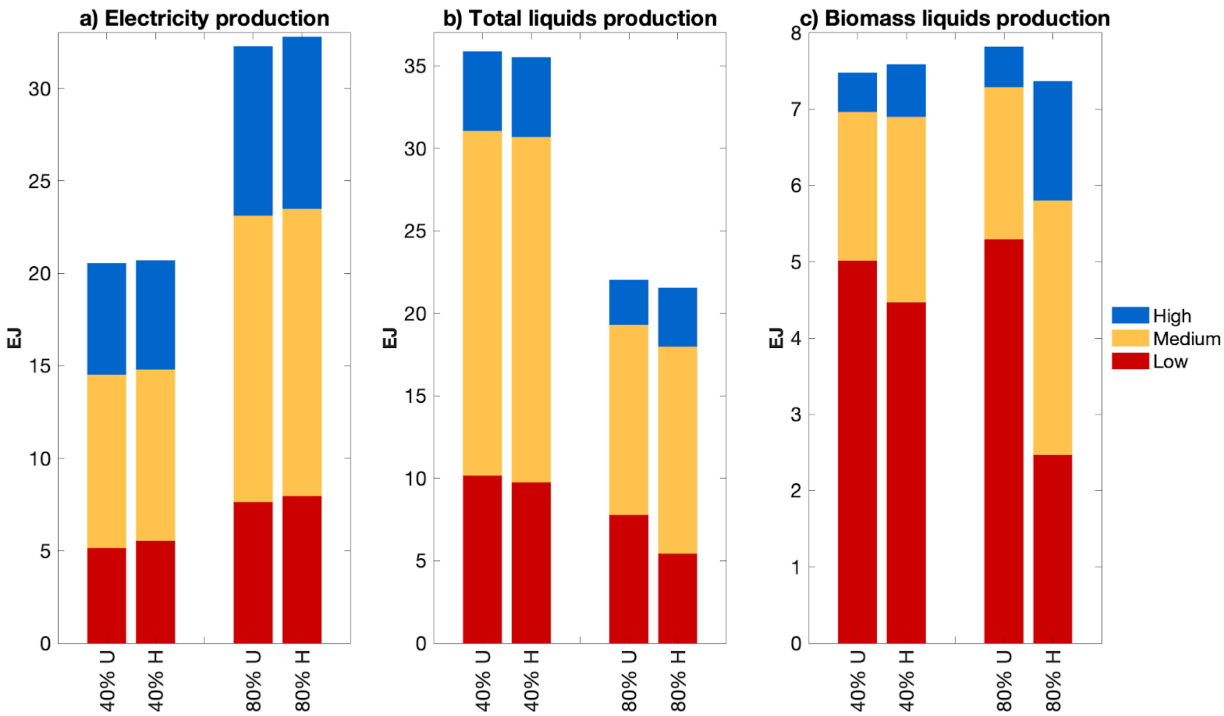
Supplementary Figure 1: National total GHG target and energy system CO_2. The "No climate policy" scenario assumes no CO_2 price. We then set targets for national total GHG (in CO_2 equivalent) in 2050 to be 20%, 40%, 60%, 80%, and 95% below 2005 level, and further assume a linear trend between 2015 and 2050. To achieve the aggregate GHG targets, we let the model solve the relative contribution of mitigation efforts in energy-related CO_2, land-use CO_2, and other non-CO_2 GHGs. As a result, the percent reductions in energy-system CO_2 are greater than the percent reduction in total GHGs (i.e., comparing panel b to panel a). This is because we impose a price only on CO_2 but many strategies to mitigate CO_2 do not co-reduce non-CO_2 GHGs. As a result, achieving 80% reduction in total GHGs requires almost 90% reduction in energy-related CO_2. Similar patterns are observed for other decarbonization targets too.



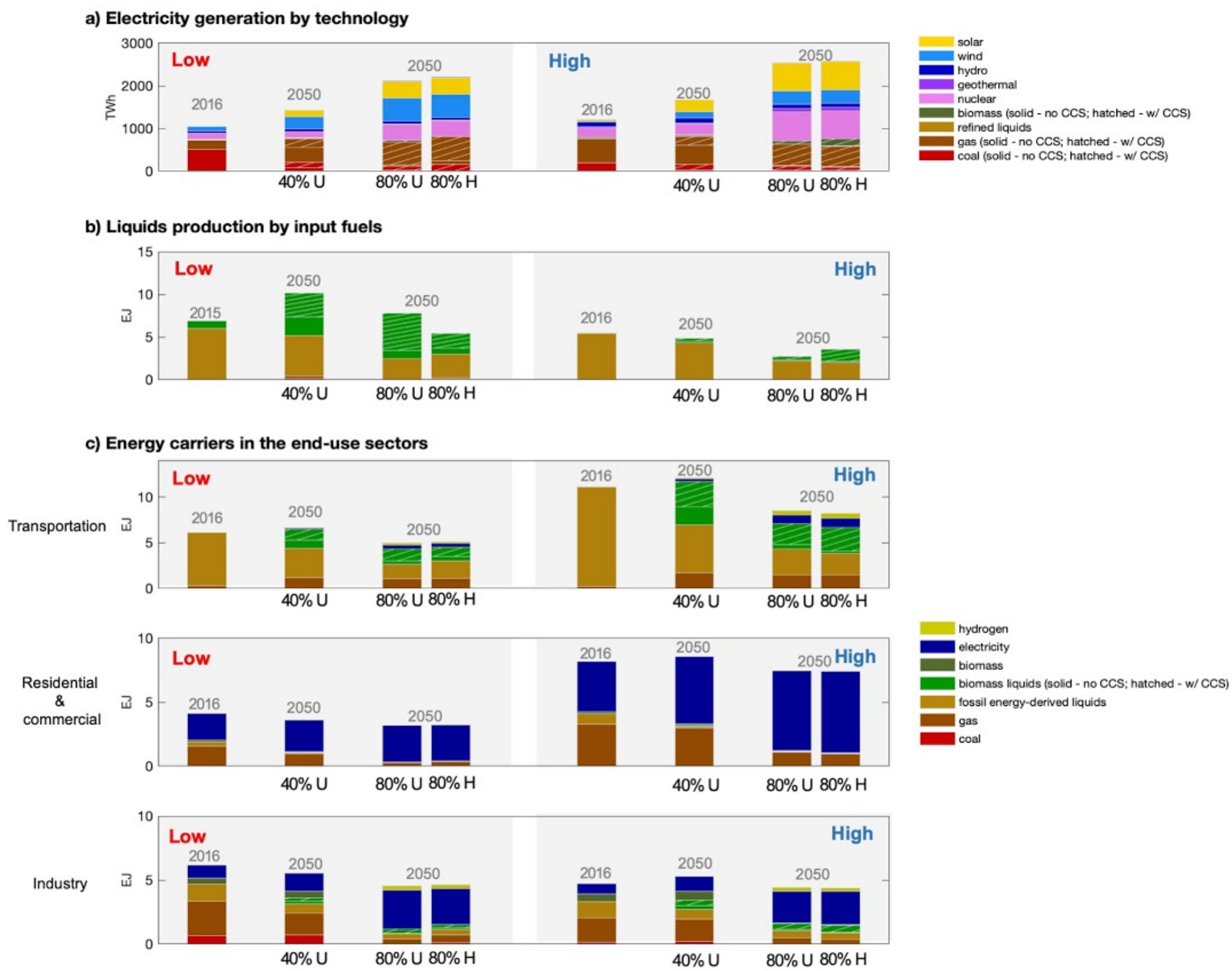
Supplementary Figure 2: National average marginal abatement cost (MAC) and national total reduction in energy-related CO2 emissions. Here the national average MAC is calculated as the weighted average of state-level MACs, with the weight being the state contribution to national total CO_2 mitigation relative to 2015 (i.e., the ratio of state-level CO_2 reduction to national total CO_2 reduction).



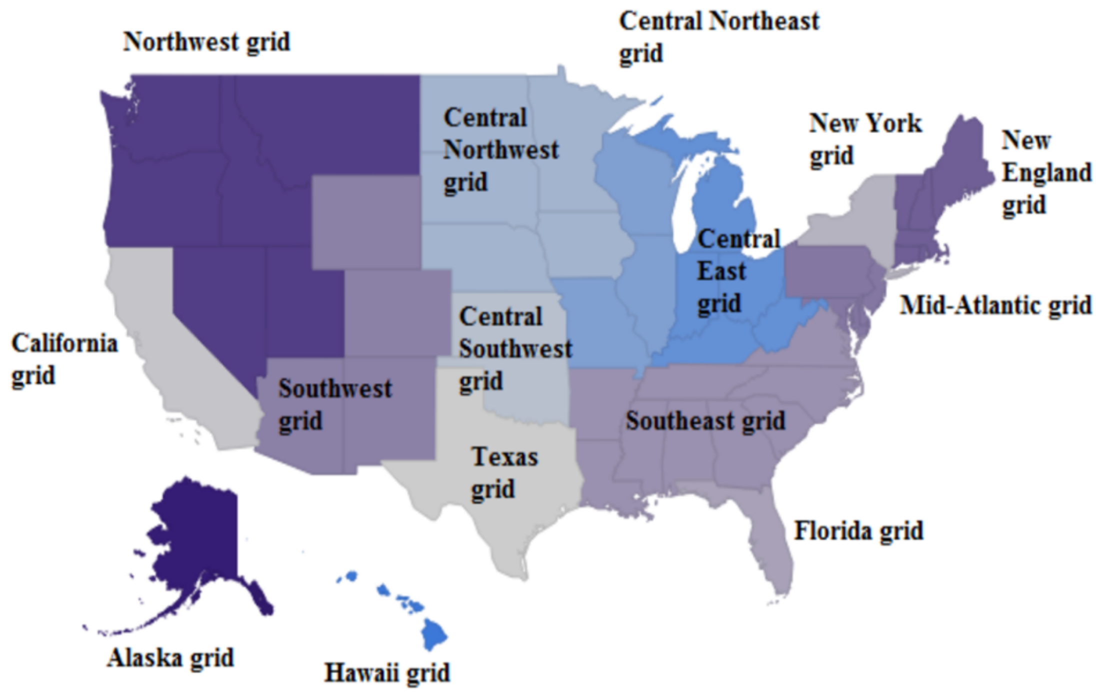
Supplementary Figure 3: Electricity and liquids production in 2050. "U" and "H" represent two subnational policy approaches: *Uniform* and *Heterogeneous*, respectively. 40% and 80% represent two levels of national mitigation effort: 40% and 80% decarbonization, respectively. "Low", "Medium", and "High" represent low-, medium-, and high-supporting states.



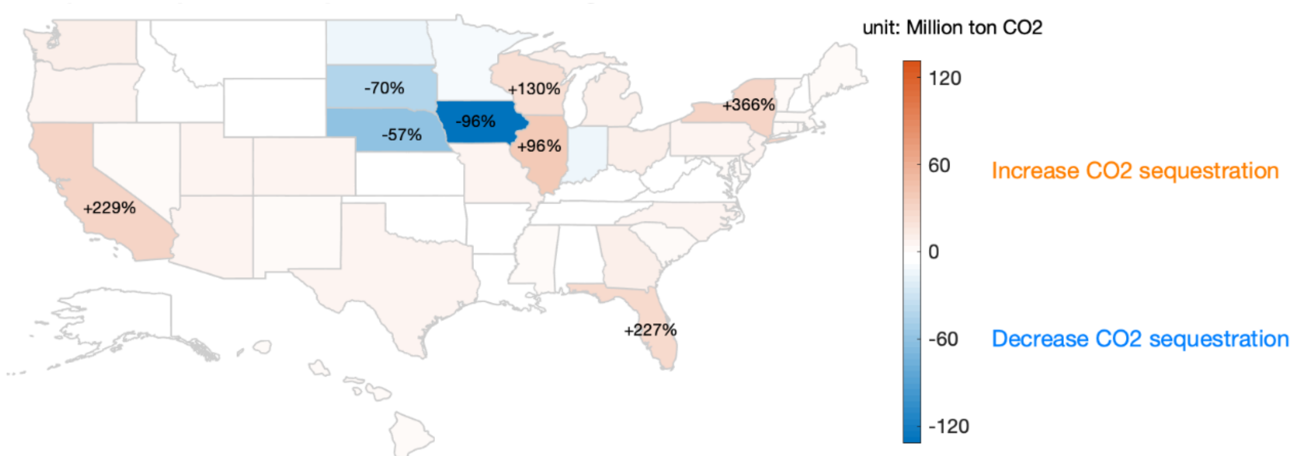
Supplementary Figure 4: Energy technology choices at present and in 2050. Panel a): Electricity generation by technology. Panel b): Liquids production by input fuel. Panel c): Energy carriers in the end-use sectors. "Low" and "High" represent low- and high-supporting states, respectively. 40% U: 40% decarbonization by 2050 nationally (relative to 2005 level) with a uniform policy approach. 80% U: 80% decarbonization with a uniform policy approach. 80% H: 80% decarbonization with a heterogeneous policy approach. The 2016 data for electricity generation and end-use energy consumption is based on EIA State Energy Data System.[18] The 2015 data for liquids production is based on state-level results from GCAM-USA.



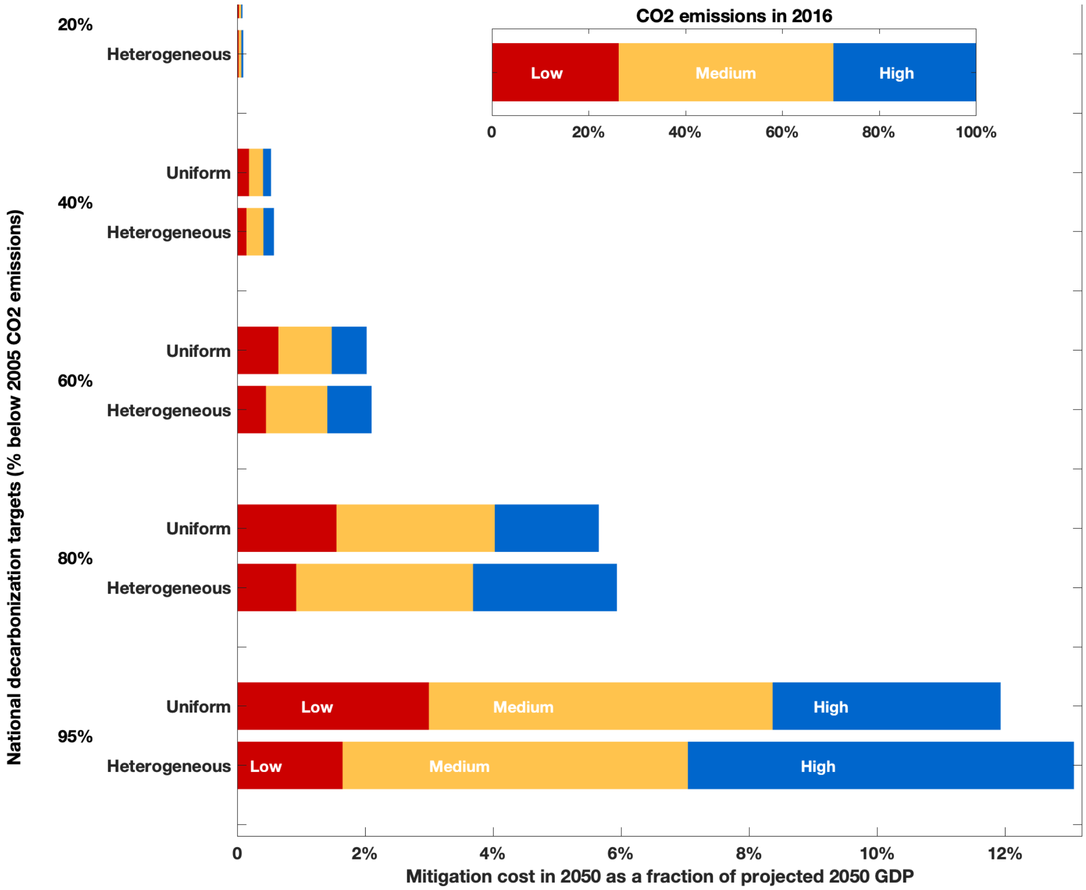
Supplementary Figure 5: Electricity grid regions modeled in GCAM-USA.



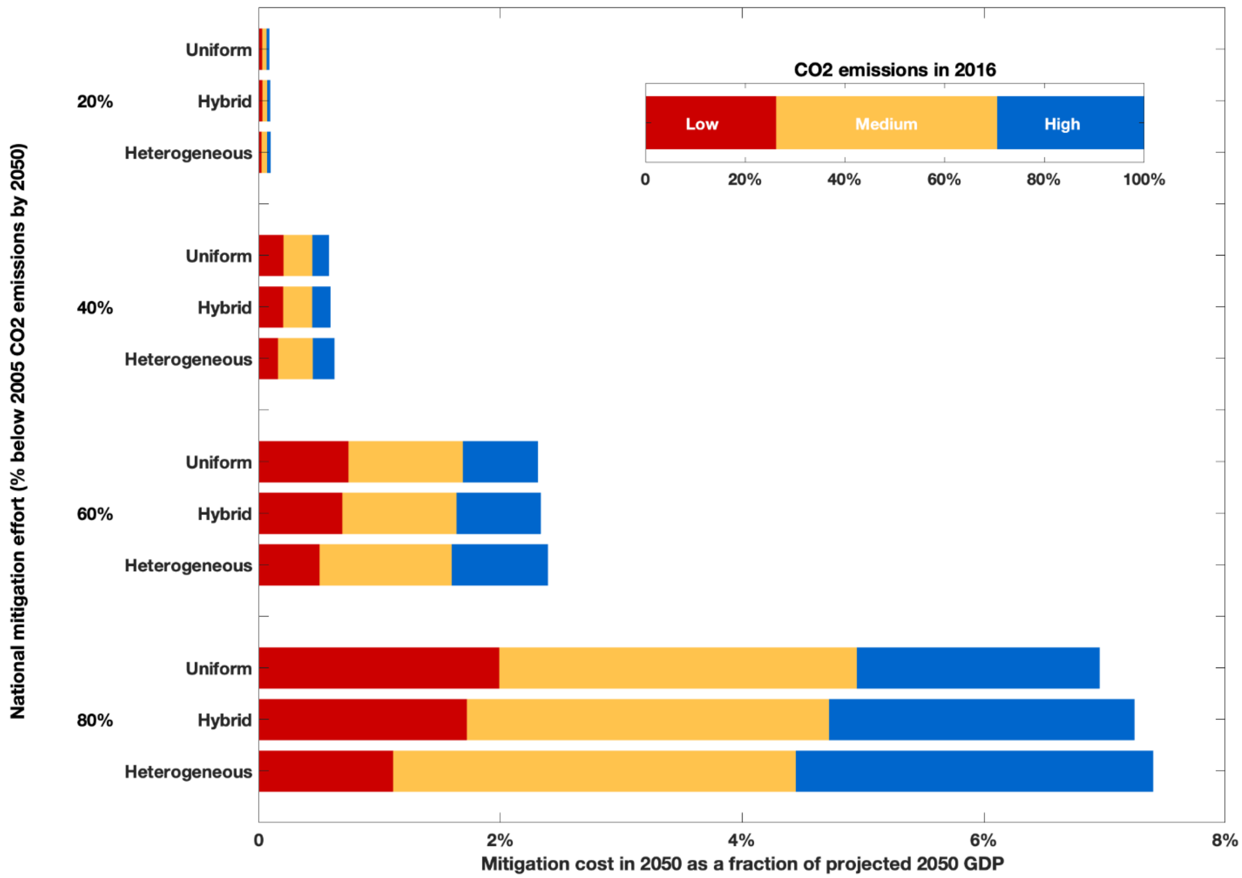
Supplementary Figure 6: To achieve 80% decarbonization nationally, state-level CO_2 sequestration by bioenergy with carbon capture and sequestration (BECCS) in 2050 under the heterogeneous approach as compared to the uniform approach. The background colors represent the absolute differences in CO_2 sequestration, and the black numbers indicate percent differences in selected states.



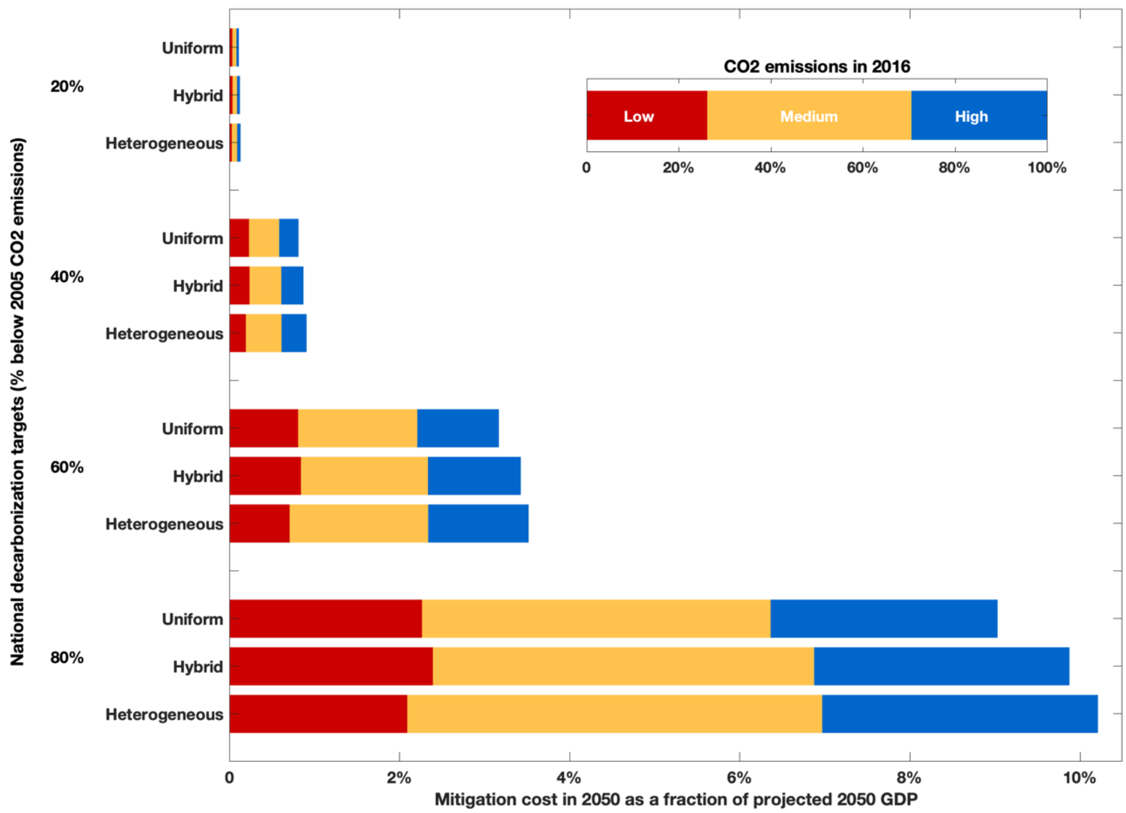
Supplementary Figure 7: Mitigation costs for 95% decarbonization. Compared to Figure 5 in the main text that shows the results from 20–80% decarbonization, here we include additional scenarios that target 95% decarbonization by 2050 relative to the 2005 level.



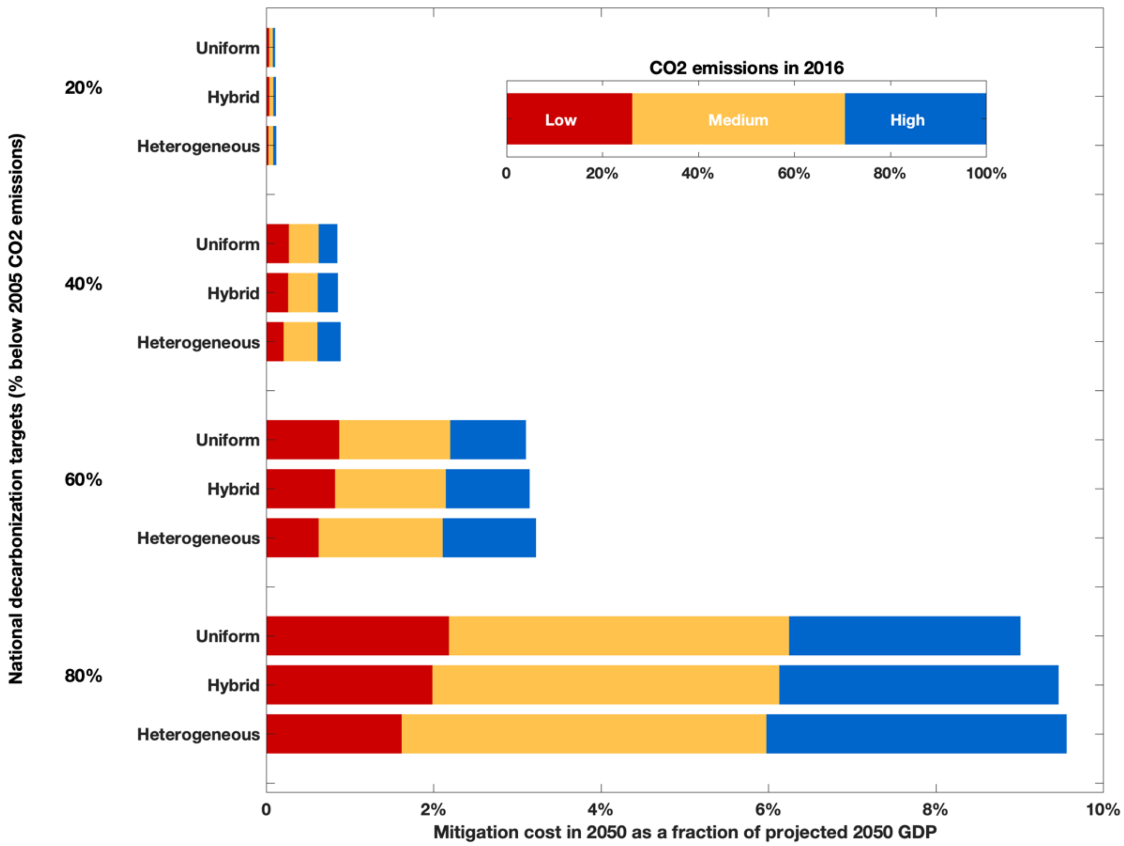
Supplementary Figure 8: Mitigation costs with the assumption of low electricity infrastructure. Here we show the carbon mitigation cost in 2050 as a fraction of projected 2050 GDP, by national mitigation effort and by subnational policy approach. Low, Medium and High-supporting states are indicated by red, yellow and blue bars, respectively.



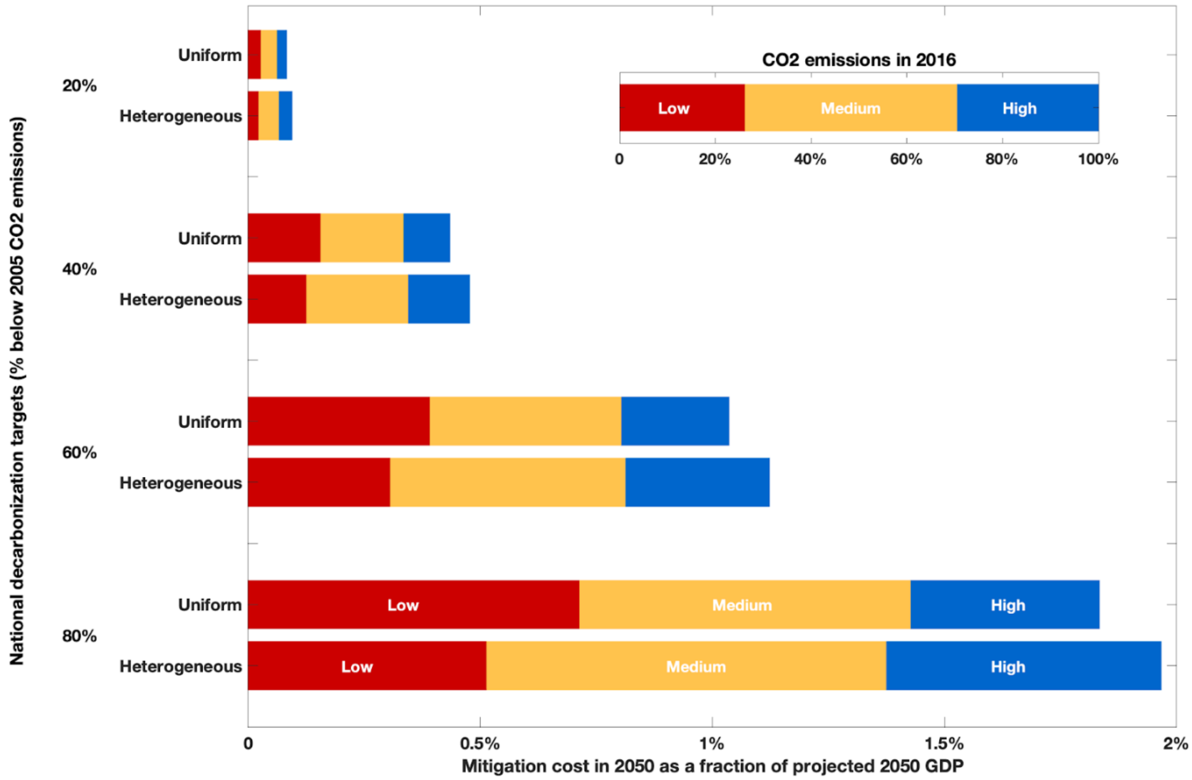
Supplementary Figure 9: Mitigation costs with the assumption of no CCS. Here we show the carbon mitigation cost in 2050 as a fraction of projected 2050 GDP, by national mitigation effort and by subnational policy approach. Low, Medium and High-supporting states are indicated by red, yellow and blue bars, respectively.



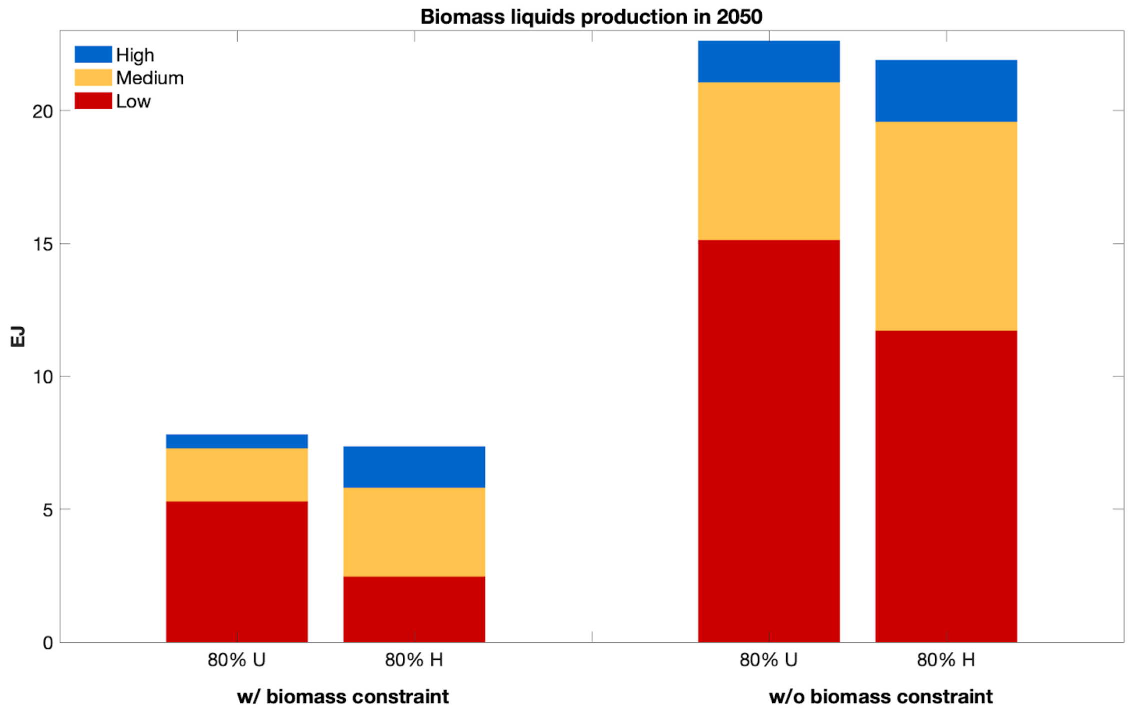
Supplementary Figure 10: Mitigation costs under low biomass availability (i.e., assumed to be half of the level in the main scenarios). Here we show the carbon mitigation cost in 2050 as a fraction of projected 2050 GDP, by national mitigation effort and by subnational policy approach. Low, Medium and High-supporting states are indicated by red, yellow and blue bars, respectively.



Supplementary Figure 11: Mitigation costs under the assumption of no biomass constraint. Here we show the carbon mitigation cost in 2050 as a fraction of projected 2050 GDP, by national mitigation effort and by subnational policy approach. Low, Medium and High-supporting states are indicated by red, yellow and blue bars, respectively.



Supplementary Figure 12: Biomass liquids production in 2050 under the assumption of no biomass constraints to achieve 80% decarbonization nationally. "U" and "H" represent the *Uniform* and *Heterogeneous* approach, respectively.



References:

1. McCright, A. M., Xiao, C. & Dunlap, R. E. Political polarization on support for government spending on environmental protection in the USA, 1974–2012. *Social Science Research* **48**, 251–260 (2014).
2. Leiserowitz, A. *et al.* Politics & Global Warming. *Yale University and George Mason University. New Haven, CT: Yale Program on Climate Change Communication* (2019) doi:DOI: 10.17605/OSF.IO/NBJGS.
3. Ballew, M. T. *et al.* Climate Change in the American Mind: Data, Tools, and Trends. *Environment: Science and Policy for Sustainable Development* **61**, 4–18 (2019).
4. Mildenberger, M., Marlon, J. R., Howe, P. D. & Leiserowitz, A. The spatial distribution of Republican and Democratic climate opinions at state and local scales. *Climatic Change* **145**, 539–548 (2017).
5. Eun Kim, S. & Urpelainen, J. Environmental public opinion in U.S. states, 1973–2012. *Environmental Politics* **27**, 89–114 (2018).
6. Leiserowitz, A. Climate change risk perception and policy preferences: The role of affect, imagery, and values. *Climatic change* **77**, 45–72 (2006).
7. Bloomberg Philanthropies, Rocky Mountain Institute & Center for Global Sustainability at the University of Maryland. Fulfilling America's Pledge: How States, Cities, and Businesses are Leading the United States to a Low-Carbon Future. (2018).
8. Tavoni, M. *et al.* Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Climate Change* **5**, 119 (2014).
9. KRIEGLER, E., TAVONI, M., RIAHI, K. & VAN VUUREN, D. P. INTRODUCING THE LIMITS SPECIAL ISSUE. *Clim. Change Econ.* **04**, 1302002 (2013).
10. Jakob, M., Luderer, G., Steckel, J., Tavoni, M. & Monjon, S. Time to act now? Assessing the costs of delaying climate measures and benefits of early action. *Climatic Change* **114**, 79–99 (2012).
11. Luderer, G. *et al.* Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters* **8**, 034033 (2013).
12. Clarke, L. *et al.* International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics* **31**, S64–S81 (2009).
13. EDMONDS, J., CLARKE, L., LURZ, J. & WISE, M. Stabilizing CO2 concentrations with incomplete international cooperation. *Climate Policy* **8**, 355–376 (2008).
14. Bosetti, V. & Victor, D. G. Politics and Economics of Second-Best Regulation of Greenhouse Gases: The Importance of Regulatory Credibility. *The Energy Journal* **32**, 1–24 (2011).
15. Iyer, G. C. *et al.* Improved representation of investment decisions in assessments of CO2 mitigation. *Nature Climate Change* **5**, 436 (2015).

16. Clarke, L. *et al.* Chapter 6 - Assessing transformation pathways. in *Climate Change 2014: Mitigation of Climate Change. IPCC Working Group III Contribution to AR5* (Cambridge University Press, 2014).

17. Howe, P. D., Mildenberger, M., Marlon, J. R. & Leiserowitz, A. Geographic variation in opinions on climate change at state and local scales in the USA. *Nature Climate Change* **5**, 596 (2015).

18. U.S. Energy Information Administration. The State Energy Data System (SEDS).