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Enhancing policy realism in energy system optimization models: Politically feasible decarbonization pathways for the United States

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ABSTRACT

In this paper, we adopt a novel approach to integrate political-organizational and techno-economic considerations to analyze decarbonization pathways for the United States. To do so, we first construct three portfolios of granular policies that target greenhouse gas (GHG) emissions reductions in the electricity, transportation, and buildings sectors, which we deem politically feasible under different federal political contexts. We then implement sectoral policy portfolios in the US-TIMES model and compare them to a business-as-usual (BAU) scenario and an 80% system-wide decarbonization scenario that uses stylized emissions constraints to produce the least-cost decarbonization pathway. Our findings reveal that greater political alignment enables electrification to play a more significant role as a central component of decarbonization. Renewable electricity generation and light-duty vehicle electrification both expand. Moreover, if the political environment allows more ambitious climate policies, deeper decarbonization can actually be achieved at a lower average abatement cost because more economically efficient policy instruments become politically feasible. However, our results indicate that none of our sectoral policy portfolios is sufficient to reduce system-wide GHG emissions by 80% by 2050. Major emissions sources for which new technologies and policies will be needed include heavy-duty vehicles, aviation, industrial production, and natural gas use in buildings.

1. Introduction

The world must significantly reduce its greenhouse gas (GHG) emissions in order to avoid the harmful impacts of climate change (IPCC, 2018). With technological advances and growth in renewable energy, models suggest that the climate goals outlined in the Paris Agreement are technically and economically achievable (Rogelj et al., 2015). However, there is disagreement over the most cost-effective technology pathways for decarbonizing entire economies, and the policies that can be enacted to deliver GHG reductions are often limited by the willingness of governments to make decarbonization a policy priority. As the largest economy in the world, the United States (U.S.) contributes roughly 15% of global GHG emissions from fossil fuel combustion and other industrial processes (Boden et al., 2017). Therefore, coming up with decarbonization pathways for the U.S. that are technically, economically, and politically feasible is important for the climate on a global scale.

Energy-economy models are widely used to analyze climate policies, develop decarbonization pathways, and assess the values and roles of key technologies. However, researchers have identified a lack of *policy realism* as a significant shortcoming of existing modeling capabilities.[1] When energy-economy models have been applied to analyze climate policies, they have overwhelmingly represented high-level “policies” such as quantity constraints on GHG emissions or carbon prices. Quantity constraints on GHG emissions allow an energy system optimization model to identify the most cost-effective technology pathway for reducing emissions, but they are really a mathematical modeling device rather than a climate policy instrument that a government could directly

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[1] In an expert poll conducted during the Macro-Energy Systems Workshop hosted by Stanford University in September 2020, experts ranked improving policy realism as the second highest priority for energy modeling research.

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implement. Furthermore, the focus of climate policy in the U.S. has moved away from an economy-wide carbon price and toward an approach based on granular, sector-specific GHG reduction policies. Researchers have propounded that climate policy modeling should better reflect social and political factors, and some have proposed high-level frameworks to improve these models (Nielsen et al., 2020; Peng et al., 2021a).

While some researchers have assessed specific policies for decarbonizing one or two sectors of the economy using energy-economy models (Shi et al., 2016; Thiel et al., 2016; Zhang et al., 2016), these studies do not capture potentially important systems-level interactions among policies that target different sectors. Policymakers need the ability to analyze combinations of sectoral policies that are designed to collectively decarbonize the whole economy. Improving policy realism in energy-economy models is thus crucial for enhancing their relevance to real-world climate policy formulation.

To address these research gaps, we incorporate a wide range of sectoral climate policies into the TIMES energy system optimization model of the United States (US-TIMES), which provides economy-wide coverage. Then, we construct three portfolios of sectoral climate policies that we deem politically feasible under three different levels of the U.S. federal government's support for reducing GHG emissions: Low Alignment, Medium Alignment, and High Alignment. Each portfolio consists of specific policy instruments (and their levels) designed to reduce emissions in the electricity, transportation, and buildings sectors. We implement these sectoral policy portfolios as scenarios in the US-TIMES model and compare them to one another as well as two benchmark scenarios: business-as-usual (BAU) and a stylized decarbonization scenario based on GHG emissions constraints that require an 80% reduction below 2010 emissions by 2050 (System80). The BAU scenario allows us to quantify the GHG abatement costs of the three sectoral policy portfolios. In the System80 scenario, we impose upper bounds on annual GHG emissions that decline linearly from the emissions level in 2010 to 80% below that level in 2050. By comparing our sectoral policy portfolio scenarios to the System80 scenario, we can elucidate any gaps between what is politically feasible and what is achievable in a purely techno-economic sense.

Our primary contribution to the literature is our integration of the techno-economic and political-organizational dimensions of decarbonization into a model-based GHG mitigation analysis. Our approach provides a politically-informed assessment of the options for deep decarbonization that studies focused exclusively on technology and economics implicitly overlook. Previous studies have tended to rely on energy-economy models to identify the most cost-effective decarbonization pathways, and then hypothesize about the specific climate policy instruments that could be enacted in practice to actually catalyze those pathways. By contrast, we explicitly represent sectoral policy instruments in the US-TIMES model and develop decarbonization scenarios that our work suggests would be politically feasible under different U.S. federal political environments. Therefore, our results can inform policymakers on the key sectoral climate policies that are likely to have the largest impact on reducing GHG emissions and to do so at modest costs.

The remainder of this paper is organized as follows. Section 2 reviews relevant literature on deep decarbonization and energy system optimization models. Section 3 details our methods, including a description of the US-TIMES model, our reference scenarios, and our policy scenarios. Model results for GHG emissions and technology and fuel mix transitions in the electricity, buildings, and transportation sectors are presented in Section 4. In Section 5, we provide more in-depth discussion of GHG abatement costs and specific sectoral policies. We conclude the paper in Section 6 by summarizing our key findings, acknowledging limitations, and offering insights into future climate policy formulation.

2. Literature review

2.1. Deep decarbonization studies

Many recent studies model pathways for deep decarbonization of the U.S. economy (Diringer et al., 2019; Haley et al., 2019; Larson et al., 2020; O'Riordan and Chakroff, 2021; Orvis and Mahajan, 2021; Williams et al., 2021). Two basic approaches have been adopted: (1) modeling based on scenarios with specific targets for emissions reductions (e.g., net-zero emissions, a percentage reduction in emissions), or (2) modeling based on scenarios with specific portfolios of policies (e.g., clean energy standards, zero-emission vehicle standards, building equipment and efficiency standards, carbon taxes). Regardless of approaches or scenarios evaluated, several principal elements have been found to be of critical importance: (1) enhancing energy efficiency in buildings, transportation, and industry; (2) decarbonizing electricity and other fuels; and (3) fuel switching of end uses to electricity and other low-carbon energy carriers. Where it is considered, land use management, particularly in agriculture and forestry, is also an important source of carbon sequestration. This wave of deep decarbonization studies has reinforced a growing consensus around the most promising policies, their relative contributions and efficiencies, and how they interact and support each other. We provide summaries of numerous deep decarbonization studies in the online Supplementary Material (SM), and focus below on the energy system modeling efforts most closely related to our own.

2.2. Energy system optimization models for decarbonization pathways

A general approach to classifying energy system models is based on the amount of detail in which technologies and commodities are represented. We can classify energy models into top-down and bottom-up models, as well as hybrid models. While top-down models focus on the overall economy via a relatively small number of aggregate variables and equations, bottom-up models contain more detailed, technology-explicit information on individual sectors of the economy.

In this study, we adopt and extend the TIMES model, a bottom-up, least-cost optimization model that has been applied to study many energy systems. Yang et al. (2015) use the CA-TIMES optimization model to study possible decarbonization pathways for California to achieve its 2050 GHG emissions target. Their findings based on BAU and a series of deep GHG emissions reduction scenarios imply that California's targeted 80% reduction below 1990 emissions can be realized at low to moderate cost. Vaillancourt et al. (2017) investigate deep decarbonization pathways for Canada using the North American TIMES Energy Model (NATEM). Their findings demonstrate the importance of electrifying end-use sectors, decarbonizing electricity generation, and making efficiency improvements. Vaillancourt et al. (2008), based on analysis with the WORLD-TIMES model, explore the role of nuclear energy in various climate scenarios.

Other studies have used TIMES to analyze policy and technological changes for decarbonizing a specific sector. Shi et al. (2016) analyze the roles of advancing technology (alternative building insulation) and the deployment of renewable energy in the buildings sector to achieve decarbonization goals using the China TIMES model. Zhang et al. (2016) use TIMES to compare decarbonization pathways in the transport sector in China and the U.S. Thiel et al. (2016) evaluate European Union (EU) carbon dioxide (CO_2) regulations using the JRC-EU-TIMES model and point out the important role of regulation in mitigating EU emissions. A more comprehensive summary of prior literature is included in the online Supplementary Material (SM).

3. Methods

3.1. US-TIMES model

TIMES is an economic model generator for energy systems developed by the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA). The TIMES model is a bottom-up, technology-rich, least-cost linear program (Loulou et al., 2005). Final demands in all energy end-use sectors are exogenously specified. Market-clearing conditions lead to partial equilibrium in energy markets to meet these demands. The model endogenously determines capacity investments in different technologies and demands for various primary energy resources and energy carriers. The model output also includes GHG and air pollutant emissions. In the TIMES model, researchers construct scenarios to explore possible energy futures (Loulou et al., 2005). A scenario consists of a collection of consistent assumptions about the future characteristics of energy system drivers.

In this study, we use the TIMES database for the U.S. energy system maintained by the Environmental Protection Agency (EPA), EPAUS9rT (Lenox, 2019). This is a nine-region database covering the U.S. commercial, industrial, electric, residential, resource supply (upstream), refinery, and transportation sectors. The database has a time horizon from 2010 to 2050, with a time step of five years (Lenox, 2019). Past and projected end-use demands are based on the Annual Energy Outlook from the Energy Information Administration (EIA) (U.S. Energy Information Administration (EIA), 2020). We refer to the TIMES model with the EPAUS9rT input database as US-TIMES. Our modeling efforts are based on a modified version of the US-TIMES model, which enables US-TIMES to envision more ambitious GHG reduction pathways (which we believe are realistic from a technical feasibility standpoint) and thus allows us to analyze deep decarbonization scenarios such as an 80% decrease in economy-wide emissions by 2050 (see Appendix A and Appendix B for more details about the input data and our modifications).

US-TIMES naturally captures the interactions (synergies and trade-offs) among climate policies implemented in individual sectors, since the model features economy-wide coverage and endogenously determines optimal technology investments and operational levels in an integrated fashion. This is a major advantage of our approach to analyzing the GHG impacts and costs of sectoral climate policies relative to off-the-shelf estimates such as McKinsey and Company (2020). Their estimates only apply to each mitigation strategy in isolation; once multiple strategies are combined to form a policy portfolio, their estimates can no longer be considered accurate. In contrast, US-TIMES accounts for the interdependencies among mitigation strategies in multiple sectors.

The objective of US-TIMES, which is to minimize the net present value of long-run, system-wide costs, is equivalent to an objective of maximizing economic surplus (Loulou et al., 2005). Environmental externalities are not directly included in the objective, but for the tax and subsidy policies that we model, tax revenues raised (subsidy expenditures) are subtracted from (added to) the system cost. All costs are discounted to the 2005 base year at a rate of 5%.[2]

3.2. Sectoral policy portfolio scenarios

In this subsection, we outline our policy scenarios based on portfolios of sectoral mitigation policies in the electricity, transportation, and buildings sectors. Ultimately, the sectoral policies that we include in these portfolios are based on compatibility between potential policy instruments and the structure of US-TIMES (i.e., which policies can be captured in the model) and an in-depth political feasibility analysis (Shidore and Busby, 2020a; b, 2021). Appendix C provides detailed characteristics of the policies modeled in the various scenarios. Below, we provide a brief summary.

Given the sharp divide on climate policy between the two main U.S. political parties, the U.S. Congress, and especially the Senate, turns out to be the key swing actor in determining which policy proposals may actually be adopted (Shidore and Busby, 2020a). Assuming a Democrat in the White House and a Democratically-controlled House,[3] we explore decarbonization pathways in three policy environments in order of increasing enthusiasm for climate action: Low Alignment, Medium Alignment, and High Alignment.

Low Alignment assumes a Senate under Republican control. Both Medium and High Alignment scenarios assume Democratic control of the Senate, but the filibuster is retained in the former, and abolished in the latter.[4] However, taxes and spending measures can be passed by a simple majority under a provision known as “budget reconciliation,” which is typically allowed only once a year.

In each scenario, we group policy elements in each sector into three categories: Mandates & Standards, Investments, and Taxes & Subsidies. Not all policies can be modeled within the scope and structure of US-TIMES, and our representations of some policy instruments in US-TIMES are stylized and imperfect proxies for real-world policies. Nonetheless, this is a useful exercise to gauge the GHG emissions impacts and associated abatement costs of a wide range of sectoral policies that have been implemented or are being given serious consideration in U.S. climate policy circles.

We define Low, Medium, and High Alignment policy portfolios that focus on the electricity, transportation, and buildings sectors. Broadly, the Low Alignment portfolio relies on tax credits, research and development (R&D), standards for federal procurement and regulations, and fossil-industry-backed strategies such as carbon capture, utilization, and storage. These measures have attracted significant Republican support in the past. The Medium Alignment portfolio includes more regulatory instruments such as sectoral carbon taxes, which have some possibility of attracting Republican support, as they are seen as market-friendly. The High Alignment portfolio relies substantially on mandates and standards such as a clean electricity standard. Tables 1–3, based on Shidore and Busby (2020a,b, 2021), summarize the three sectoral policy portfolios and our modeling choices on which policy elements they include.

The political feasibility analysis drew on Congressional legislation records (including content and sponsorship of bills that were proposed but never voted upon) and news reports to identify the suite of policies that were actively under discussion in Washington. These broadly fell under three emergent policy priorities among climate activists: standards, investments, and environmental justice. When the analysis was started prior to the 2020 election, a Democratic presidency was deemed likely. It was also assumed that the Democrats would retain control of the House of Representatives. The scenarios, therefore, hinged upon which party would control the Senate.

The team identified three possible scenarios for Senate control which would have a meaningful impact on the passage of climate legislation: the Republicans retaining a majority (a Low Alignment scenario), the Democrats achieving a narrow majority with no change in filibuster rules (a Medium Alignment scenario), and the Democrats achieving a majority with elimination of the filibuster (a High Alignment scenario). We then assessed which policies enjoyed broad bipartisan support, which had potential support from a limited number of Republicans to pass with filibuster rules unchanged, and which might attract a narrow majority of Democrats, including swing or “red” state Democratic Senators such as Joe Manchin of West Virginia and Kyrsten Sinema of

[2] For detailed information on the EPAUS9rT input database, see Lenox et al. (2013).

[3] We do not explore scenarios with a Republican president as, under the current circumstances within the Republican Party, this likely leads to a trivial outcome of minimal or no federal climate action.

[4] The filibusteris a unique feature of U.S. politics in which a super-majority of 60 votes is needed to pass most legislation in the Senate.

Table 1
Electricity sector policies considered and included in the three portfolios.

Policy Type	Policy Proposal	Low Alignment	Medium Alignment	High Alignment	Political Feasibility	Modeling Choice
Mandates & Standards	Federal clean electricity standard			✓	Medium	✓
	Climate risk disclosure for public companies		?	✓	Medium	
	National energy efficiency resource standard		✓	✓	Medium	✓
	Curbs on hydraulic fracturing				Low	
Investments	Inter-state transmission	?	✓	✓	High	
	RD&D in clean energy innovation	✓	✓	✓	High	✓
Taxes & Subsidies	PTC/ITC extension	?	✓	✓	High	✓
	CCS tax credit extension/enhancement	✓	✓	✓	High	✓
	Carbon price (tax or cap-and-trade)		?	✓	Medium	✓
	Storage policy incentives		?	✓	Medium	
	Fossil fuel subsidies reduction or elimination			?	Low	

Table 2
Transportation sector policies considered and included in the three portfolios.

Policy Type	Policy Proposal	Low Alignment	Medium Alignment	High Alignment	Political Feasibility	Modeling Choice
Mandates & Standards	ZEV mandate		?	✓	Medium	✓
	Tougher fuel economy standard (regulatory)	✓	✓	✓	High	✓
	ZEV standard for federal fleets (regulatory)	✓	✓	✓	High	✓
Investments	Charging station infrastructure	✓	✓	✓	High	
	Domestic ZEV manufacturing and strategic mining	✓	✓	✓	High	
	Mass transit and low-carbon mobility	?	?	✓	Medium	✓
Taxes & Subsidies	ZEV tax credit extension/enhancement	?	✓	✓	High	✓
	ZEV rebates		?	✓	Medium	
	Pollution tax on fossil fuel vehicles			?	Low	✓
	Federal gas tax increase				Low	

Table 3
Buildings sector policies considered and included in the three portfolios.

Policy Type	Policy Proposal	Low Alignment	Medium Alignment	High Alignment	Political Feasibility	Modeling Choice
Mandates & Standards	Building energy performance standards	✓	✓	✓	High	✓
	Enhanced appliance standards	?	✓	✓	Medium	✓
	Faircloth Amendment repeal		?	?	Low	
Investments	Sustainable home construction and retrofits	?	✓	✓	Medium	✓
	Weatherization Assistance Program enhancement	✓	✓	✓	High	✓
	Enhanced efficiency of federal buildings	✓	✓	✓	High	✓
	Smart city investments	?	✓	✓	Medium	✓
	Training investments	✓	✓	✓	High	
Taxes & Subsidies	25C, 45L revival/enhancement	✓	✓	✓	High	
	Solar ITC extension	✓	✓	✓	High	✓
	Tax credits for home electrification	?	?	?	Low	✓

Arizona (who were among the four such senators specifically identified). There was some discussion of the budget reconciliation process which was mooted as one way to circumvent the filibuster process.[5]

There is broad agreement that the technologies needed to substantially reduce industrial sector emissions are by and large not yet commercially available, and will require more research, development, and demonstration to achieve meaningful scale (Mikunda et al., 2014). For this reason, we do not model policies specific to the industrial sector, but we do consider whether policies in other sectors affect industrial emissions (e.g., via electrification and decarbonization of electricity).

[5] Note that as of writing (November 10, 2021), the political environment in Washington was roughly consistent with our Medium Alignment scenario. The bipartisan Infrastructure Investment and Jobs Act had just passed, but President Biden's Build Back Better agenda had yet to pass Congress.

4. Results

In this section, we present results from US-TIMES, focusing on comparisons between the three sectoral policy portfolio scenarios and the BAU and System80 scenarios. We first report results for GHG emissions, then analyze how the technology and fuel mixes evolve in each sector under the five scenarios. Comparing the scenario results provides insights into the GHG reduction potentials of various policy elements and highlights areas where additional policies will be needed to achieve deeper decarbonization goals.

4.1. GHG emissions

Fig. 1 plots system-wide GHG emissions in all five scenarios. In addition, Table 4 shows the percentage change in GHG emissions from 2010 to 2050 in each sector and system-wide under each scenario. Overall, compared to BAU, all three sectoral policy portfolios lead to lower emissions throughout the entire timeframe. By 2050, the GHG emissions reductions relative to 2010 in the Low, Medium, and High

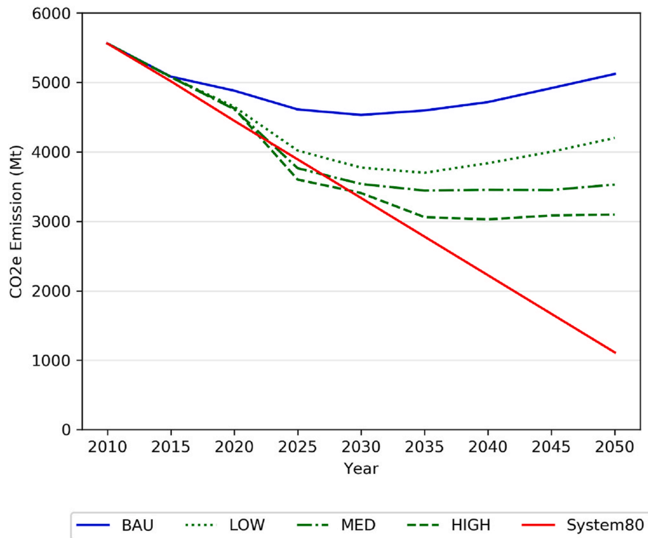

Fig. 1. System-wide GHG emissions in all scenarios.

Table 4
Sectoral and system-wide GHG emissions reductions from 2010 to 2050 in all scenarios (negative for an emissions reduction, positive for an emissions increase).

	BAU	System80	LOW	MED	HIGH
Buildings	−49.3%	−82.6%	−49.1%	−53.4%	−52.1%
Electricity	−49.9%	−96.8%	−52.4%	−80.0%	−96.7%
Industrial	79.3%	−69.3%	67.0%	60.5%	60.4%
Transportation	1.2%	−66.5%	−39.7%	−40.1%	−45.4%
System-wide	−7.9%	−80.0%	−24.4%	−36.5%	−44.3%

Alignment scenarios are 24.4%, 36.5%, and 44.3%, respectively. Therefore, the portfolios of sectoral mitigation policies that we deem technically and politically feasible do not appear capable of reducing economy-wide GHG emissions by 80% by 2050.

Interestingly, 2050 is not the year with the lowest emissions in the BAU and sectoral policy portfolio scenarios. In the BAU case, system-wide GHG emissions decline from 5562 Mt in the base year 2010 to 4532 Mt in 2030, then increase to 5124 Mt in 2050. The three sectoral policy portfolios also lead to U-shaped emissions trajectories, but relative to BAU, their emissions decline more significantly in the near-term and do not increase as sharply after 2035 (except for Low Alignment). System-wide emissions reach minimum values of 3699 Mt (2035), 3442 Mt (2035), and 3028 Mt (2040) in the Low, Medium, and High Alignment scenarios, respectively. In all three sectoral policy portfolio scenarios, many of the policies are implemented starting in 2020; thus we see the most substantial GHG reductions from 2020 to 2025, relative to BAU. GHG reductions in the Medium and High Alignment scenarios briefly outpace the straight-line reduction path of the System80 scenario from 2020 to 2025. It is important to note that the policies included in our portfolios are based on static assessments of current technical and political feasibility, and this largely explains why their emissions-reducing effects saturate around 2035 or 2040. Ultimately, emissions begin to rise again due to the unavailability of new technologies, limitations on efficiency enhancements of current technologies, and increasing demand for energy services in end-use sectors. It is certainly possible that other (or more stringent) policies could become technically and politically viable between now and 2050.

Fig. 2, which illustrates the evolution and sectoral composition of GHG emissions in each scenario, reveals several interesting findings: (1) the electricity sector is the first to experience substantial reductions in GHG emissions; (2) decarbonization in the transportation sector plays a significant role in achieving deeper GHG reductions, and the transportation policies that we include in the sectoral policy portfolios continue to reduce transportation GHG emissions throughout the model timeframe; and (3) GHG emissions from the buildings sector remain relatively steady compared to emissions from other sectors. Relative to BAU, the electricity sector undergoes steep reductions in GHG emissions from 2020 to 2030 in the other four scenarios. As suggested by the Medium Alignment plot, the carbon tax in the electricity sector (assumed to be \$20/tCO_2e) reduces emissions from 2025 to 2030, but this policy ceases to be effective beyond 2030, when the tax is not high enough to incentivize further decarbonization. In the High Alignment scenario, with the inclusion of a clean electricity standard by 2035, the electricity sector continues to contribute to decarbonization from 2030 to 2035, which is in line with the System80 scenario. It is worth noting again that in our sectoral policy portfolio scenarios, there are no specific policies addressing emissions from the industrial sector directly. The System80 scenario reveals that industrial-sector GHG reduction in the most cost-effective pathway to an 80% reduction in system-wide emissions contributes about 17% of the overall reduction, but in our sectoral policy portfolio scenarios, the absence of industrial-sector-specific policies leads industrial emissions to increase.

4.2. Electricity sector

Decarbonization of the electricity sector plays an indispensable role in decarbonizing the entire economy (Fig. 2). The electricity sector features cost-effective mitigation opportunities, and reducing GHG emissions from other sectors may rely heavily on electrification.

Fig. 3 shows the evolving electricity generation mixes in all scenarios. Comparing the sectoral policy portfolio results with BAU, it is evident that extensive infrastructure transformation will have to take place in the electricity sector. Renewables play an increasingly vital role in power generation for years beyond 2030 in all sectoral policy portfolio scenarios. Another finding is that total power generation is significantly higher in the System80 scenario, since it involves more electrification in the transportation and buildings sectors. In 2050, total generation levels in the BAU, High Alignment, and System80 scenarios are 16,280, 21,048, and 36,837 PJ, respectively. Coal is not entirely phased out in any of the scenarios, a somewhat surprising finding that may be due to technical rigidities embedded in US-TIMES. In the Low Alignment scenario, natural gas generation increases over time, while in Medium Alignment, natural gas generation decreases significantly after 2030 as a result of implementing a national energy efficiency resource standard (mainly on the use of natural gas) and a \$20 carbon tax in the electricity sector. In the High Alignment scenario, the clean electricity standard drives natural gas use in power generation downward, leading to a minimal share of natural gas generation after 2035. The role of nuclear power remains negligible throughout the entire timeframe, except in the System80 scenario, where nuclear generation in 2050 is three times higher than it is under BAU.

The installed capacity results in Fig. 4 reveal similar policy impacts. The clean electricity standard's inclusion in the High Alignment portfolio leads to a rapid expansion of renewables from 2030 to 2035. The total renewable capacity in 2050 in the High Alignment scenario is 3.18 times that under BAU. Fig. 5, which visualizes the evolving fuel mixes in the electricity sector, points to many of the same themes. It is worth noting that the High Alignment scenario includes 1422 PJ of biomass consumption for power generation in 2050; System80 is the only other scenario that features biomass in the electricity fuel mix (though the shares are low).

4.3. Transportation sector

Fig. 6 illustrates the evolution of the transportation sector fuel mix in each scenario. The U.S. Energy Information Administration (EIA) (2020) projects that travel demand will continue to increase over time, but this

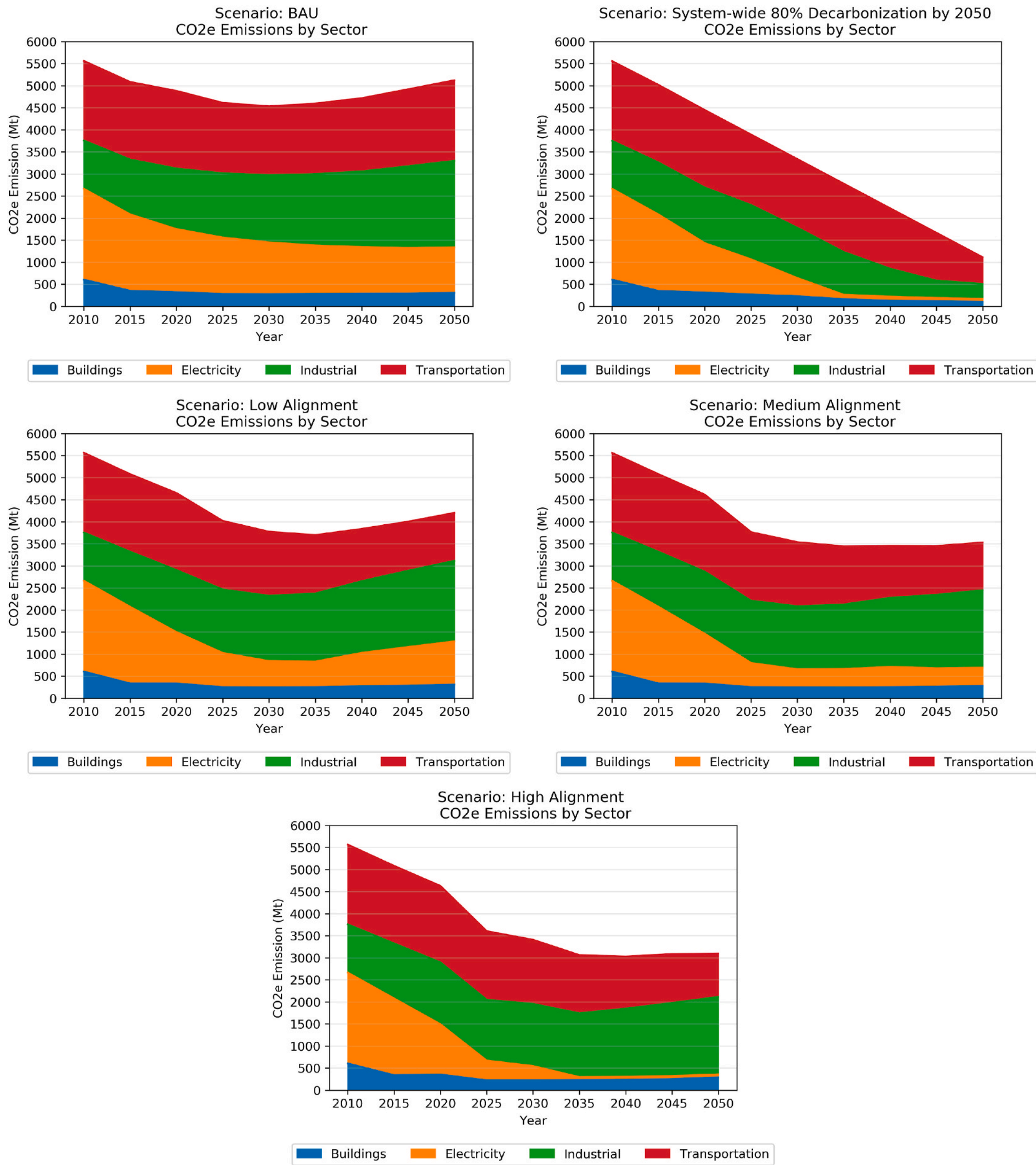

Fig. 2. Sectoral GHG emissions in all scenarios.

can be offset by efficiency improvements in terms of the total energy demand in the transportation sector. Under BAU, transportation energy demand is essentially the same in 2050 as it was in 2010, and the fuel mix does not exhibit any significant changes. Gasoline remains the dominant transportation fuel for the entire timeframe, though its share of energy consumption drops from 63.3% in 2010 to 50.7% in 2050. By contrast, the four other scenarios all display significant electrification that displaces gasoline consumption in the transportation sector, a transition that really accelerates after 2030. In the High Alignment scenario, the share of electricity in the transportation fuel mix increases from 1.1% in 2010 to 24.6% in 2050, whereas gasoline's share falls from 63.3% to 6.2%.

Given projected reductions in EV investment costs, the combination of more stringent corporate average fuel economy (CAFE) standards and a zero emission vehicle (ZEV) tax credit in the Low Alignment scenario is sufficient to enable electrification in 2035. The ZEV mandate (in the Medium and High Alignment scenarios) enhances this electrification trend. Electricity's share in the transportation fuel mix increases from 1.7% in 2030 to 5.3% and 6.0% in 2035 in the Low and Medium Alignment scenarios, respectively. In the High Alignment scenario, the ZEV mandate for medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs) imposed in 2045 leads to a significant increase in electricity consumption from 2045 to 2050, compared to Medium Alignment. Electricity's share of transportation energy consumption increases from 17.4% in 2045 to 20.8% and 24.6% in 2050 in the Medium and High Alignment scenarios, respectively. In the System80 case, the electrification trend begins slightly later than in the sectoral policy portfolio scenarios, but by 2050, System80 features the largest electricity share in transportation (36.4%, see Fig. 8).

Changes in the consumption of diesel for transportation also offer insights for policymaking. Fig. 7 summarizes diesel consumption in various scenarios from 2020 to 2050. Diesel use declines to 2037 PJ by 2050 in the System80 scenario, but remains high in the sectoral policy portfolio scenarios, reaching 6871 PJ in 2050 even in the High Alignment scenario. This is only slightly below the diesel use of 7101 PJ in the BAU case. From 2020 to 2040, diesel consumption in the Medium and High Alignment scenarios is consistent with the System80 scenario – diesel consumption in all three scenarios is slightly higher than the BAU scenario with an increasing trend. In the System80 scenario, we observe a substantial decrease in diesel consumption from 2040 to 2050. This

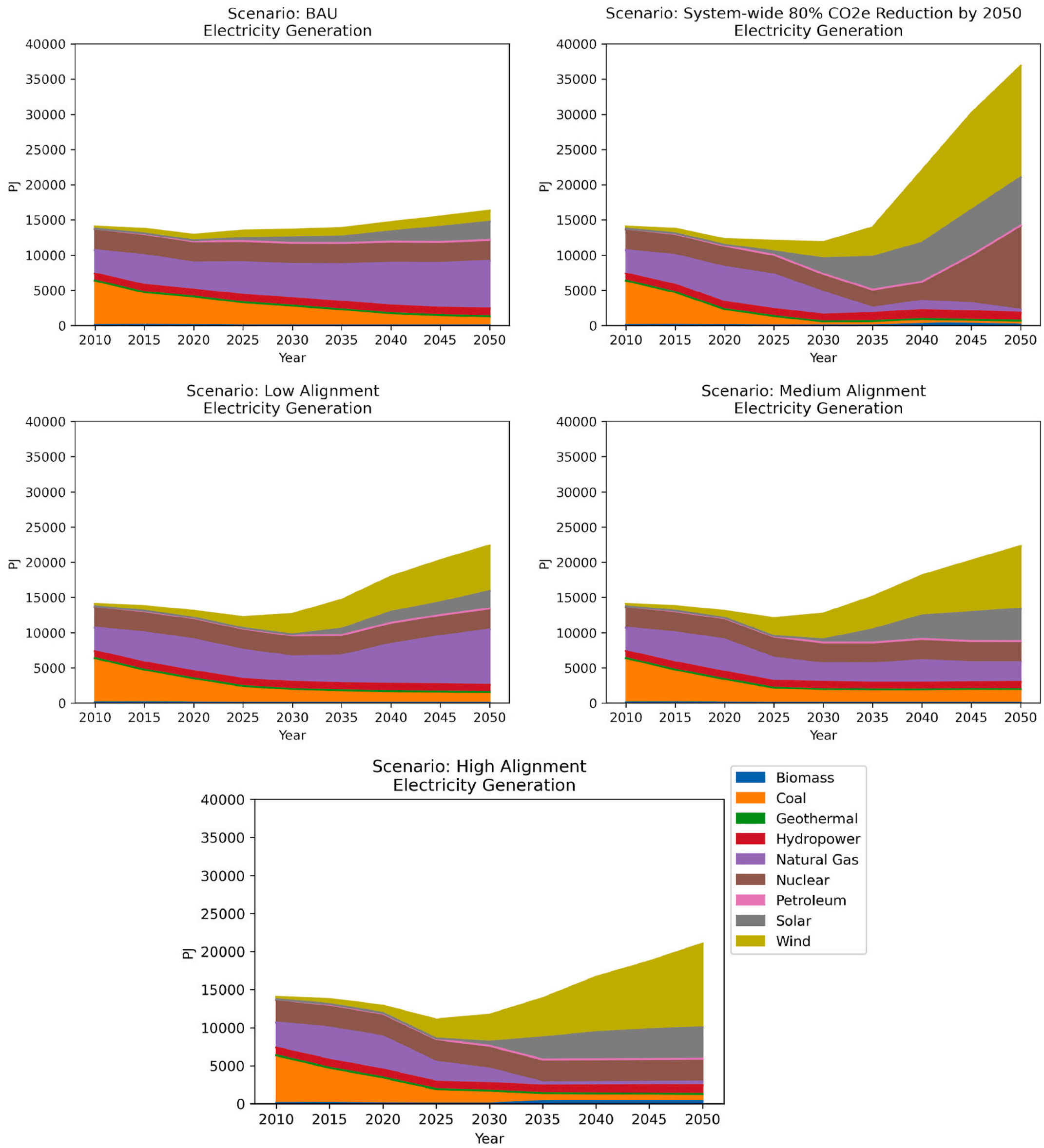

Fig. 3. Electricity sector generation mixes in all scenarios.

reduction in diesel consumption is evidently part of the optimal pathway for complying with the increasingly stringent GHG reduction targets as 2050 (and its 80% reduction target) approaches. However, the comparison between the Medium and High Alignment scenarios from 2045 to 2050 suggests that without concerted efforts to substitute for diesel use by trucks, emissions reductions achieved through the electrification of light-duty vehicles (LDVs) will be somewhat offset by higher emissions from trucks. As we mentioned earlier, the ZEV mandate for MDVs and HDVs introduced in 2045 in the High Alignment scenario broadens the transportation sector's electrification trend and begins to reduce diesel consumption. Given that the sectoral policy portfolio scenarios differ only with respect to the policies that they apply, we can infer that the decrease in diesel consumption from 2045 to 2050 in the High Alignment scenario is induced by the additional policies included in the High Alignment portfolio, but not in the Medium Alignment portfolio. In addition, note that the mass transit investment policy in the High Alignment scenario diverts some travel demand from LDVs to buses, which could run on diesel unless complementary policies are implemented to make them cleaner. The ZEV mandate for MDVs and HDVs also serves this purpose.

Fig. 8 shows the transportation fuel mixes in 2050 in all scenarios. In contrast to BAU, electricity, diesel, and jet fuel account for most transportation energy consumption in all three sectoral policy portfolio scenarios. These transitions in the transportation fuel mix are aided by efficiency improvements that reduce total energy demand in the sector. Relative to the most cost-effective deep decarbonization pathway in the System80 scenario, the sectoral policy portfolios struggle to address diesel use by MDVs and HDVs. A deeper decarbonization target requires additional policies to decarbonize MDVs and HDVs sooner and more extensively. The System80 scenario is the only one that features an increase in biofuel use, with a noticeable increase from 2030 to 2035 in Fig. 6 and the largest share in 2050 in Fig. 8.

4.4. Buildings sector

Fig. 9 shows the buildings sector fuel mixes in all scenarios. Across all scenarios, we observe a slight electrification trend in the buildings sector for 2025 and beyond, with a clearer upward trend in the System80 scenario. This is because the policy portfolios mandate efficiency improvements in electric appliances and buildings themselves, leading to lower electricity demand in the buildings sector compared to System80. While efficiency improvements play an important role in buildings-

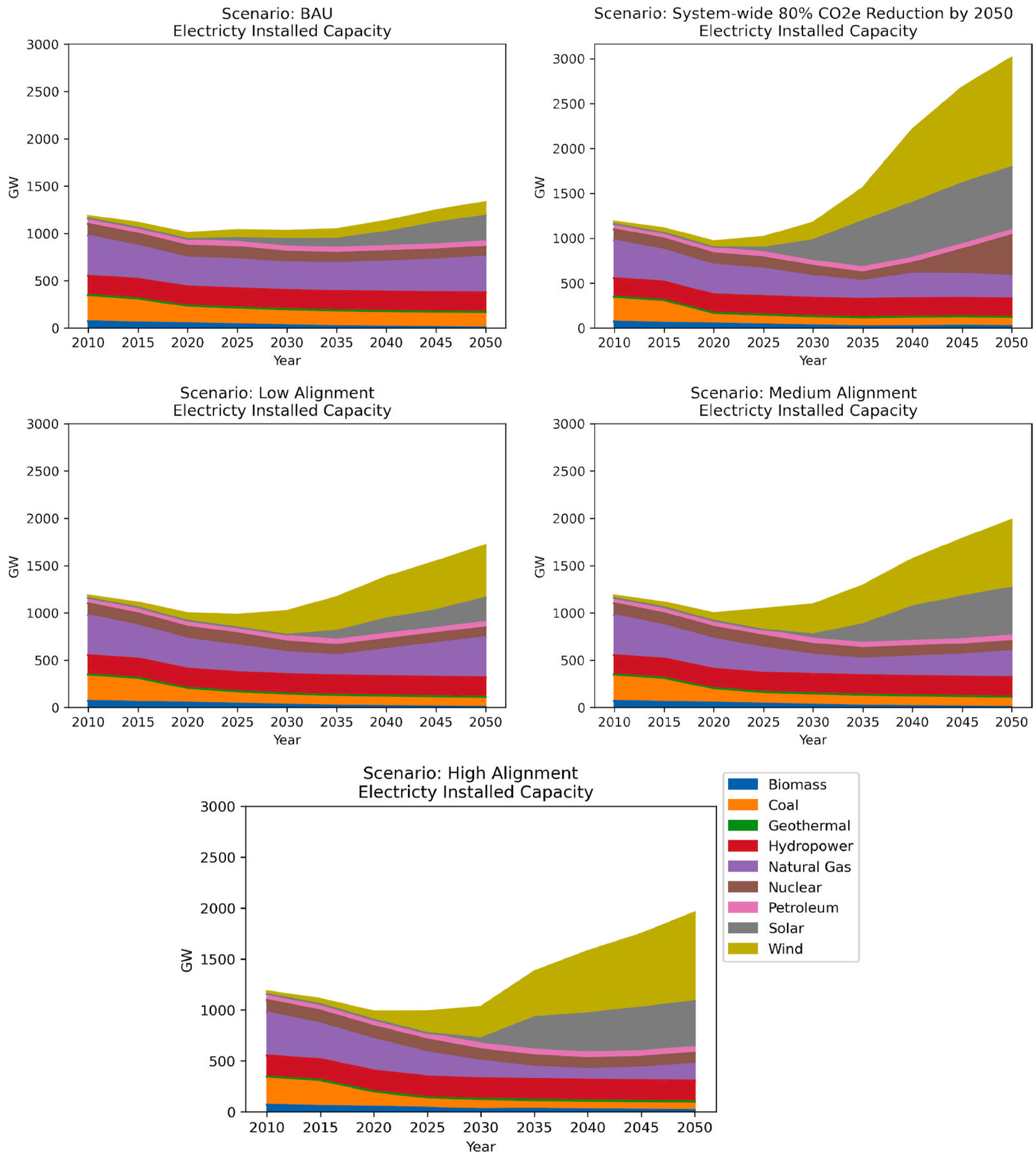

Fig. 4. Electricity sector capacity mixes in all scenarios.

sector decarbonization under all three sectoral policy portfolio scenarios, the High Alignment portfolio includes the most stringent efficiency standards and results in the lowest building energy consumption in 2050.

In all sectoral policy portfolio scenarios, natural gas is displaced by electricity from 2020 to 2025, but gas consumption in the buildings sector declines only slightly from that point forward. By contrast, natural gas use continues to decrease significantly after 2025 in the System80 scenario, and occupies a very small share of the building energy mix by 2050. Interestingly, the System80 pathway begins displacing natural gas by directly leveraging renewable energy in buildings, then shifts to a strategy of substituting electricity for natural gas. Most of the buildings sector policies that we model focus on demand reduction (e.g., space heating and cooling) via appliance and building energy efficiency improvements. The only policy that encourages renewables deployment in the buildings sector is the solar investment tax credit (ITC), and its effect is clearly not strong enough to induce the level of direct renewable energy consumption observed in the buildings sector in the least-cost pathway to an 80% economy-wide GHG emissions reduction.

As an experiment, we run two variants of the Low Alignment scenario: one in which we omit all buildings sector policies, and another where the only buildings sector policies are the solar ITC and the tax credit for home electrification. Fig. 10 illustrates how buildings sector GHG emissions in these two additional scenarios compare to those in the Low Alignment and BAU scenarios. As seen in Fig. 10, without policies to reduce building energy use (e.g., building energy performance standards, appliance standards, weatherization assistance), implementing mitigation policies in other sectors actually results in higher buildings sector emissions than in the BAU case. This highlights the importance of interactions among sectors. For example, making electricity more costly by implementing electricity sector decarbonization policies discourages electrification of building energy end-uses, and other end-use sectors such as transportation that are affected by climate policy compete with the buildings sector for clean electricity.

4.5. Industrial sector

Even though our policy portfolios do not feature any policies that specifically target the industrial sector, Fig. 11 illustrates the industrial sector fuel mixes in all scenarios. The System80 scenario is the only one

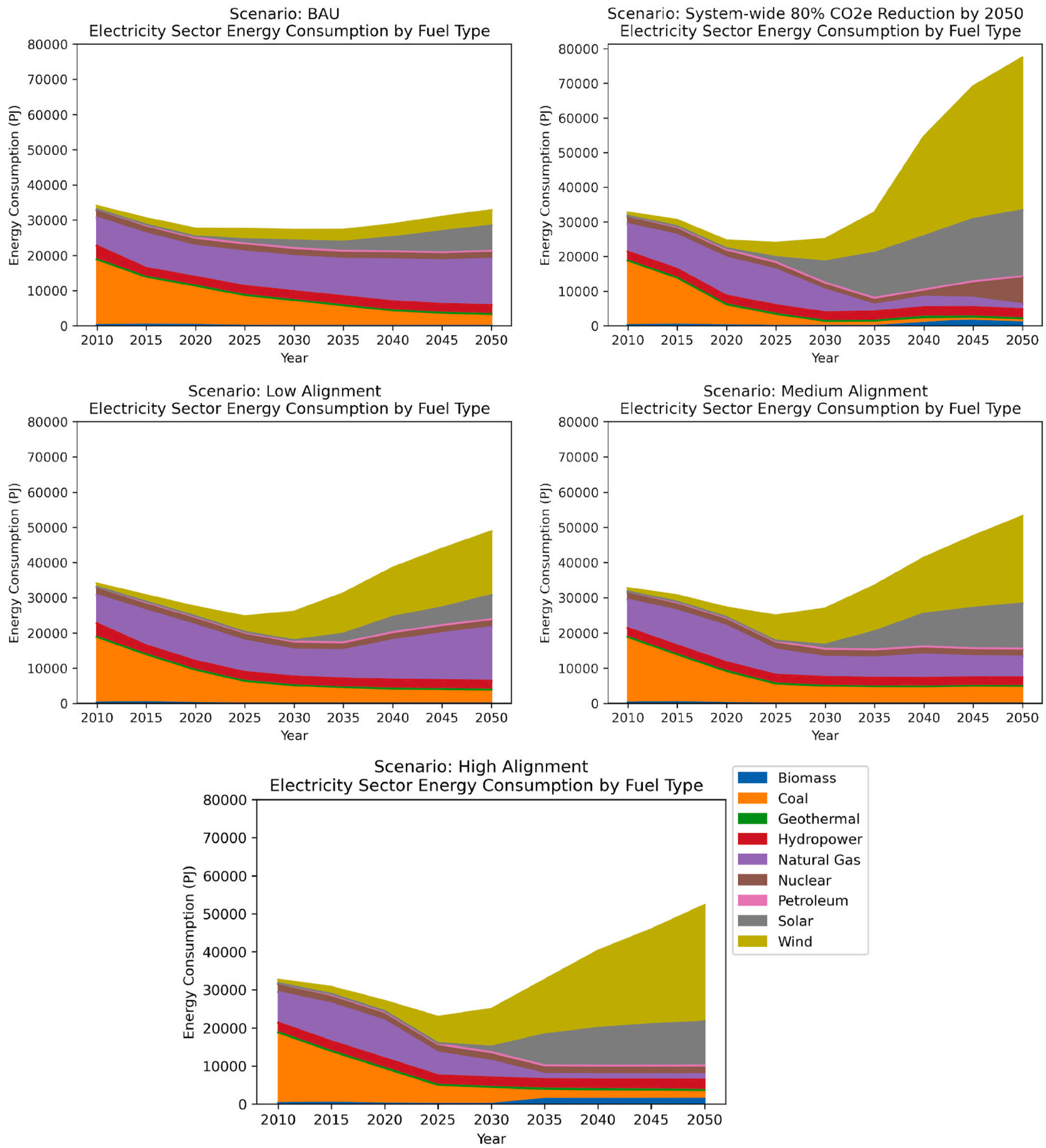

Fig. 5. Electricity sector energy consumption by fuel type in all scenarios.

with below-2010 industrial GHG emissions in 2050. This is unsurprising, because unlike the sectoral policy portfolios that ignore the industrial sector, the economy-wide emissions constraint in System80 provides an incentive to decarbonize industry. However, the very large difference between 2050 industrial emissions in System80 and in the sectoral policy portfolio scenarios is striking. From 2010 to 2050, industrial emissions decline by 69.3% in System80 but actually increase by at least 60% in the sectoral policy portfolio cases (see Table 4). These results echo other recent studies suggesting that U.S. industrial emissions could significantly increase in the near future (Waxman et al., 2020), and demonstrate the need for new technologies and policies for decarbonizing industry.

Industrial sector decarbonization in the System80 scenario primarily occurs through electrification beginning in 2035. Increasing electricity consumption displaces nearly all natural gas from the fuel mix by 2050. Total energy demand in the industrial sector in 2050 is highest under System80 (56,817 PJ), likely because electric heat for industrial processes is less efficient than gas heat. The Low Alignment portfolio reduces industrial energy consumption to 50,234 PJ in 2050, but fossil fuels dominate the industrial sector fuel mix in all of the sectoral policy portfolio scenarios. Again, this is to be expected given that the portfolios do not include any policies that target industrial sector emissions.

5. Discussion

In this section, we provide more in-depth discussions of key results, focusing on GHG abatement costs, carbon capture and sequestration (CCS), and the effectiveness of individual sectoral policies.

5.1. GHG abatement costs

To compare the cost-effectiveness of achieving decarbonization via different policy approaches, we calculate the average abatement cost (AAC) of GHG emissions reductions in the sectoral policy portfolio scenarios and in System80. To calculate the AAC, we first compute the total abatement cost (TAC) as the difference between the minimized system cost (i.e., the objective value of US-TIMES) in each scenario and that in BAU. Then, we divide the TAC by the difference between their cumulative GHG emissions over the full model timeframe to obtain the AAC, which is in units of dollars per ton of CO_2e emissions reduction achieved.

As a limitation, it is important to note that US-TIMES does not

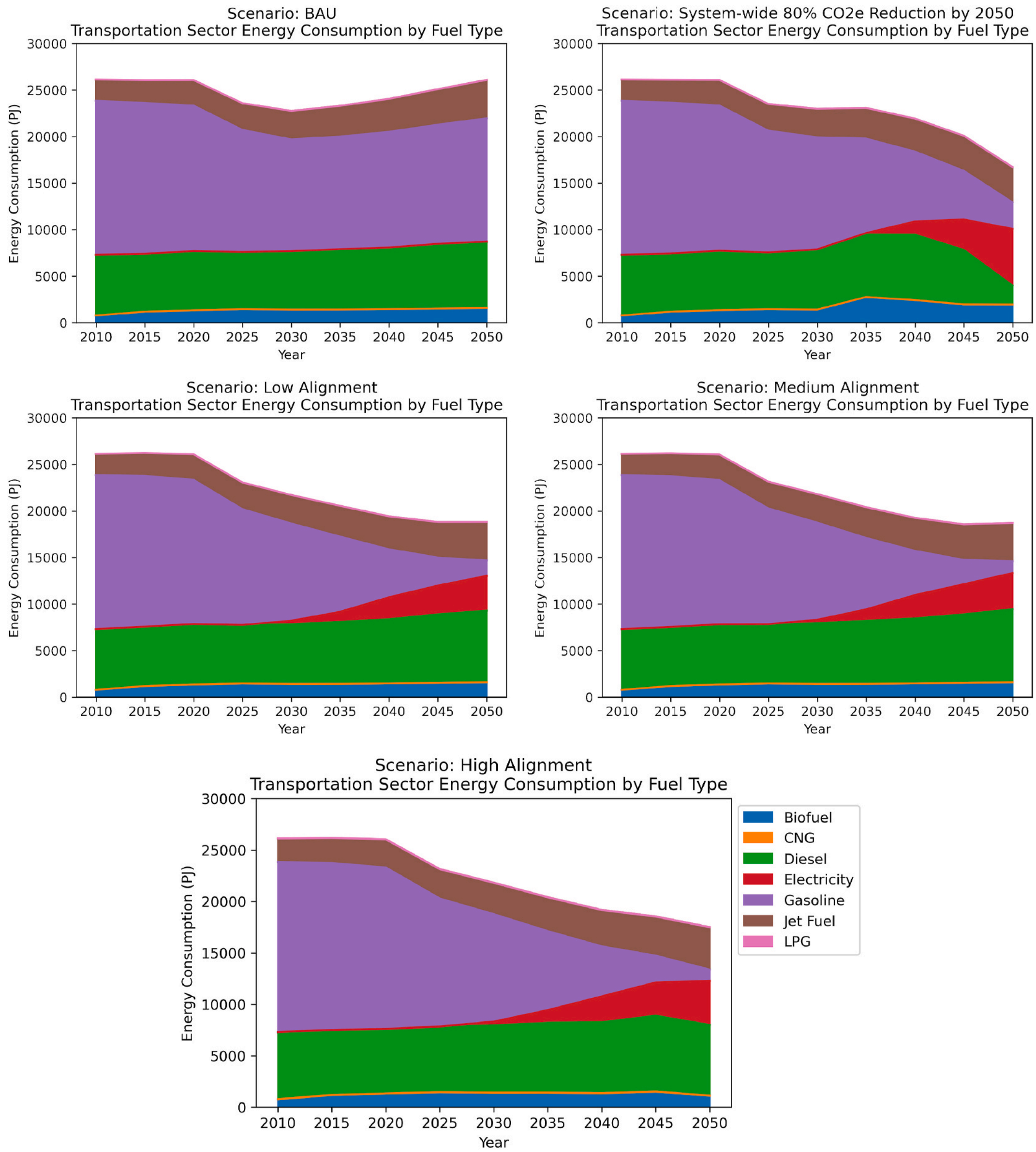

Fig. 6. Transportation sector energy consumption by fuel type in all scenarios.

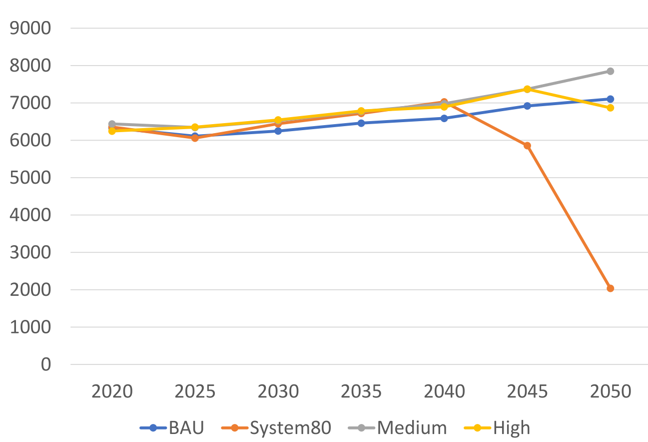

Fig. 7. Diesel consumption in various scenarios (PJ).

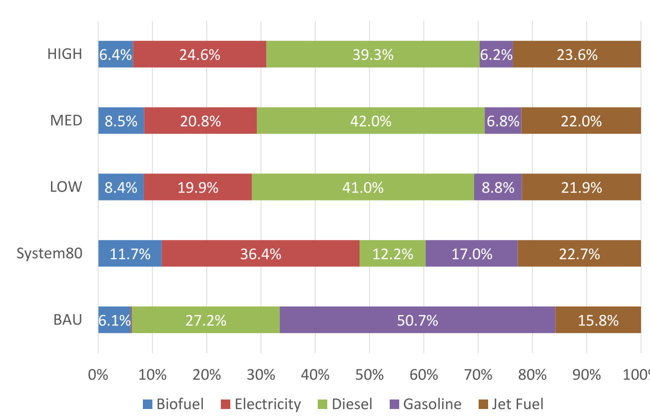

Fig. 8. Shares of transportation sector fuel consumption in 2050 in all scenarios.

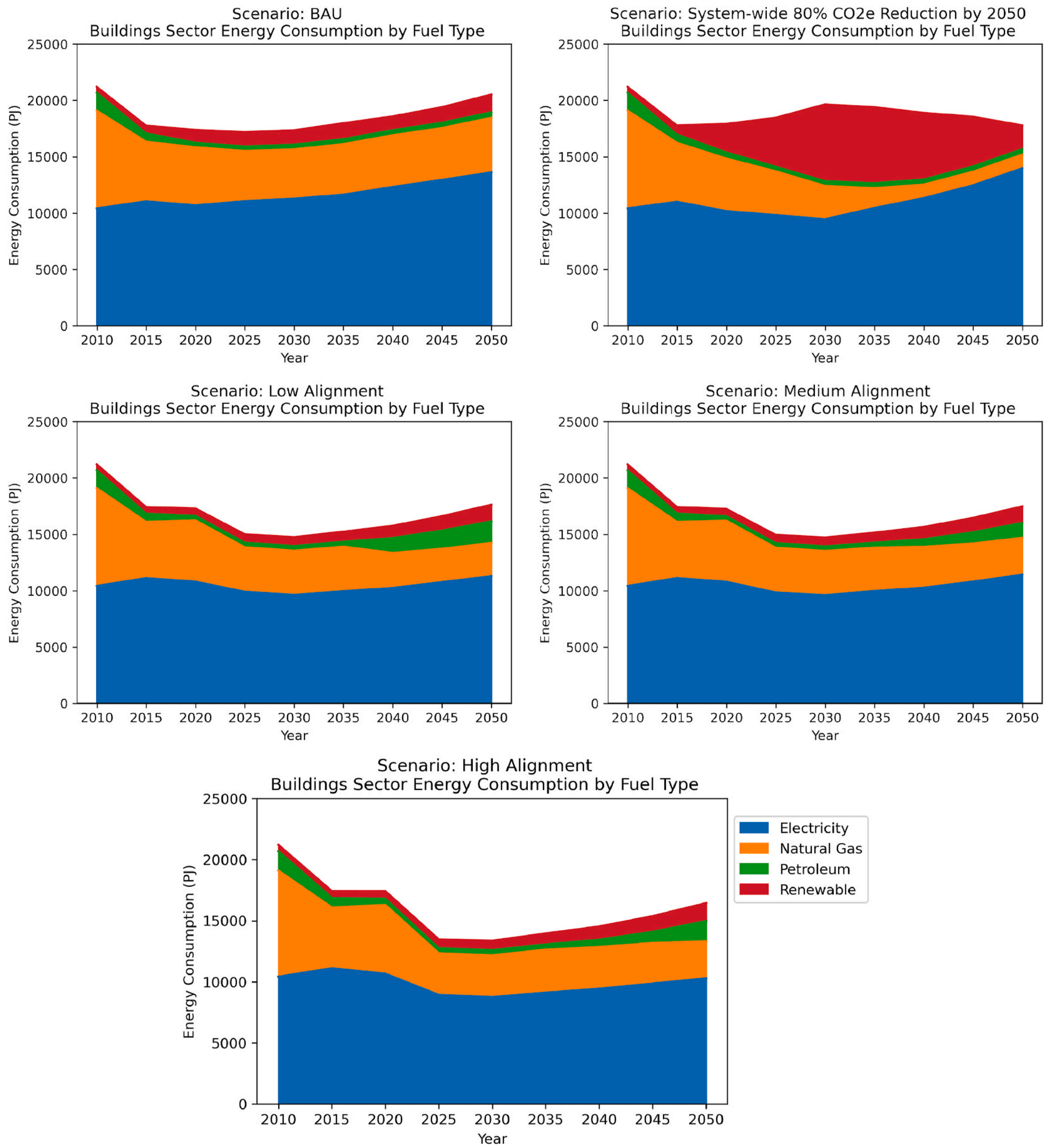

Fig. 9. Buildings sector energy consumption by fuel type in all scenarios.

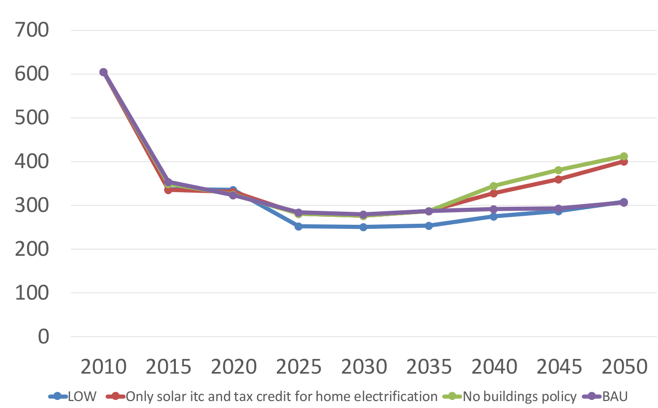

Fig. 10. Buildings sector GHG emissions in the Low Alignment and BAU scenarios, as well as two additional variants of Low Alignment that are described in the text (Mt).

capture the full costs of some policies that we model. For example, the mass transit and low-carbon mobility policies in the High Alignment scenario are represented in a stylized fashion as shifting travel demand from LDVs to bus and rail modes (Appendix B). The cost of realizing this mode shift in the real world could be substantial, but would be very hard to quantify as it would involve many specific transit projects in U.S. cities, changes in urban land use patterns, and so on. Therefore, it is not included in US-TIMES. While we acknowledge that this limitation does affect our AAC estimates, it is still valuable to investigate the relative abatement costs of different policy approaches. Note, however, that we do incorporate the revenues raised (costs incurred) due to the modeled tax (subsidy) policies into the US-TIMES objective function. For example, the solar ITC reduces the investment costs of the relevant solar technologies, but the costs of offering these tax credits are directly accounted for in the objective function. Similarly, the costs of standards such as ZEV mandates, appliance standards, and CAFE standards are naturally captured by US-TIMES, as these policies force the model to endogenously select cleaner or more efficient – but also more costly – technologies.

Relative to BAU, the GHG emissions reductions achieved in System80 come at an AAC of \$35.6/tCO_2e. For the Low, Medium, and High

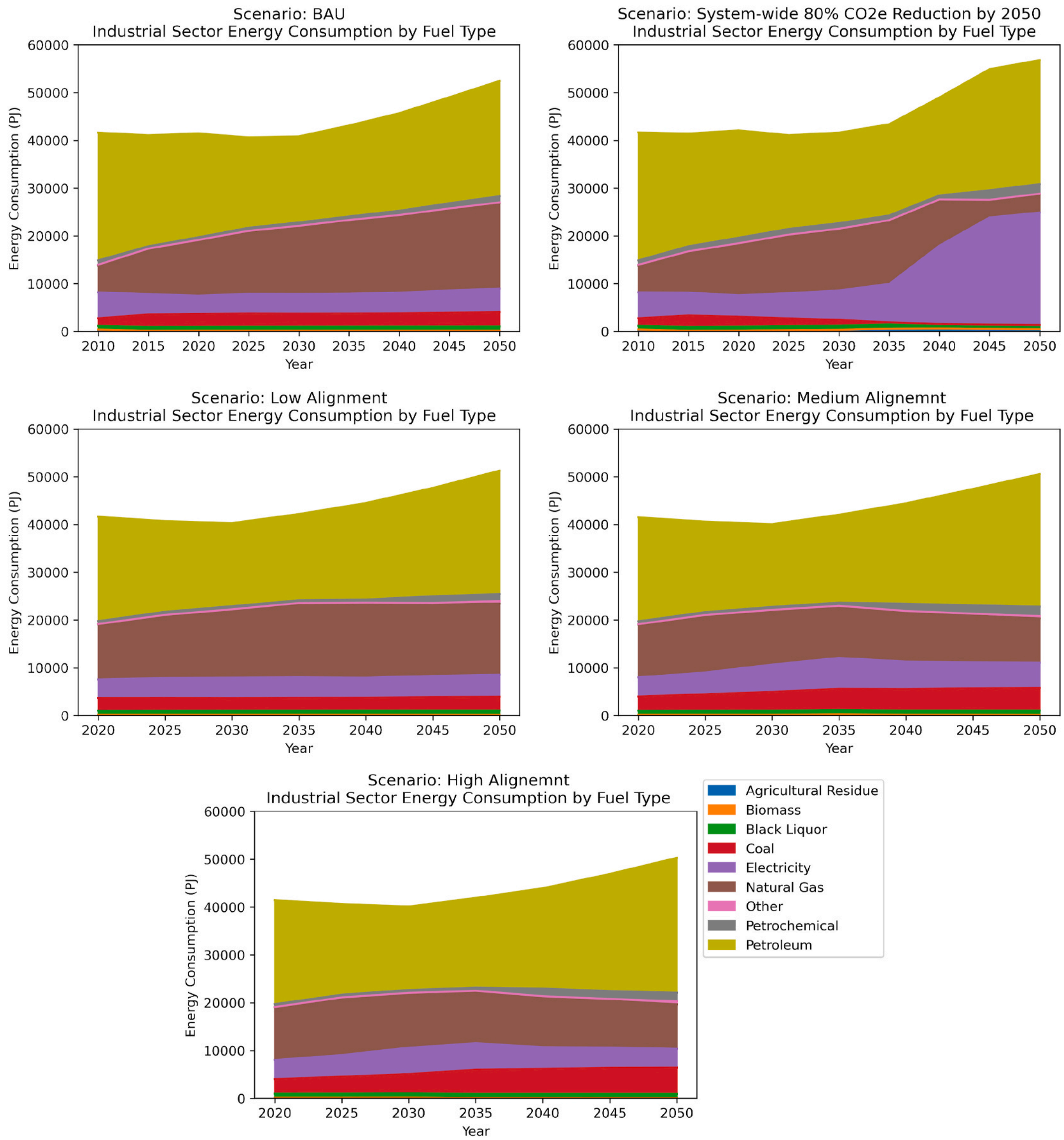

Fig. 11. Industrial sector energy consumption by fuel type in all scenarios.

Alignment sectoral policy portfolios, the AAC values are \$16.2, \$15.8, and \$12.8/tCO_2e, respectively. These AACs are not directly comparable because all four scenarios yield different reductions in cumulative GHG emissions. While the System80 scenario is, by definition, the most cost-effective pathway for reducing economy-wide emissions by 80%, its AAC is higher than those of the sectoral policy portfolio scenarios because it leads to much greater GHG reductions.

To create more natural comparisons, we run three scenarios designed to lead to the same exact cumulative GHG emissions as the three sectoral policy portfolios, but to do so based on simple emissions constraints (similar to that in System80) rather than collections of granular policies. These stylized emissions constraint scenarios achieve the same emissions reductions as their corresponding sectoral policy portfolio scenarios, but do so at lower AACs that can serve as benchmarks for judging the relative cost-effectiveness of each sectoral policy portfolio.

Fig. 12 compares the AACs of the sectoral policy portfolios to those of their corresponding stylized emissions constraint scenarios. Consistent with economic theory, when emissions constraints are tightened to decrease cumulative emissions from their Low to Medium to High Alignment levels, the AAC increases from \$3.9 to \$5.9 to \$7.8/tCO_2e. What is fascinating is that the AACs in the sectoral policy portfolio scenarios exhibit the opposite trend; achieving greater GHG reductions through the High Alignment portfolio actually comes at a lower AAC than achieving lower GHG reductions through the Medium Alignment portfolio (and the same is true for Medium vs. Low Alignment). These results reveal that if the political environment shifts to render more climate policies politically feasible, these newly viable policy instruments tend to be more cost-effective. The end result is that the political process can simultaneously deliver deeper decarbonization and lower costs per ton. Another way of looking at this is to say that some politically appealing polices are not very cost-effective, leaving some low-hanging fruit (from an economic perspective) should the High Alignment policies be adopted and implemented first.

On the other hand, in a relative sense, pursuing decarbonization using portfolios of sectoral policies is considerably more costly than reducing GHG emissions by following the least-cost pathway. Compared to their corresponding AAC benchmarks calculated from the scenarios with stylized emissions constraints, the AACs associated with the Low, Medium, and High Alignment portfolios are 4.1, 2.7, and 1.6 times higher. In line with the discussion above, the gap between the sectoral policy portfolio AACs and the stylized emissions constraint AACs narrows with stronger climate policy alignment that enables more cost-effective sectoral policy instruments. Lastly, note that the AACs in the sectoral policy portfolio scenarios are still quite low relative to social

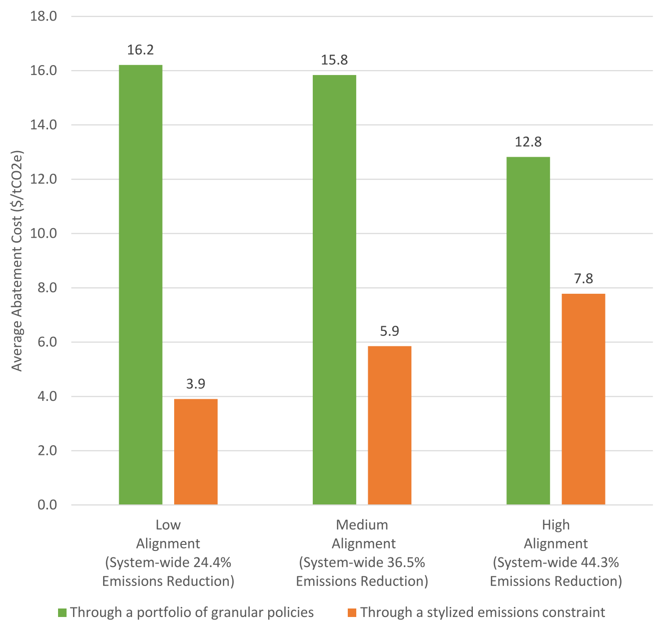

Fig. 12. Average abatement cost in various scenarios relative to the BAU scenario.

cost of carbon (SCC) estimates (Interagency Working Group on Social Cost of Greenhouse Gases, 2021), and these estimates are likely to rise substantially in the near future (Voosen, 2021), so implementing many of these policies could certainly produce net benefits even if they are not least-cost.

5.2. Carbon capture and sequestration

CO_2 capture in the US-TIMES model is considered for centralized production technologies of natural gas steam methane reforming, coal gasification, and biomass gasification systems (CCS technologies) (Lenox et al., 2013). It also includes CO_2 capture retrofit options for all new coal steam technologies, existing coal plants, as well as new IGCC (Integrated Gasification Combined Cycle) and new NGCC (Natural Gas Combined Cycle) capacity. As these technologies are represented in the electricity sector module, we have accounted for all CO_2 sequestered as part of the electricity sector GHG emissions. Fig. 13 illustrates the CO_2e produced by electricity generation (in orange), the CO_2 sequestered using new CCS technologies (in yellow), the CO_2 sequestered from retrofitted facilities (in green), and the overall CO_2 sequestered (in blue) in four scenarios (there is no record of any CO_2 sequestered in the BAU scenario).

Unsurprisingly, the tax credit for CCS leads to use of CCS, as we can observe in all of the sectoral policy portfolio scenarios. The model favors CO_2 capture retrofits due to their relatively lower costs. It is only after the clean electricity standard is implemented (in 2035) in the High Alignment scenario that new CCS technology is used to capture CO_2. Compared to all of the sectoral policy portfolio scenarios, the CO_2 sequestered in the System80 scenario is lower, since the least-cost pathway evidently relies more heavily on renewables and nuclear for power generation.

It is noteworthy that the value of the tax credit ($30/t$CO_2$ sequestered) was set by experimenting with various values. In Fig. 14, we summarize the electricity sector CO_2e emissions with various CCS tax credit values (and where the CCS tax credit is the only policy implemented). All the tax credits are applied from 2020 to 2050. The "25–50" label refers to a $25/t$CO_2$ sequestered tax credit that is implemented in 2025, and then rises linearly to $50/t$CO_2$ sequestered in 2050. Interestingly, we observe cases where a higher CCS tax credit leads to higher CO_2e emissions in the electricity sector. In these instances, the emissions-increasing effects of the CCS tax credit effectively subsidizing power generation using fossil fuels are stronger than the emissions-decreasing effects of capturing some (i.e., less than 100%) of the CO_2 from fossil-based power plants. This finding highlights the importance of considering rebound effects induced by incentives for carbon mitigation strategies.

Fig. 13. Electricity sector CO_2e emissions and CO_2 sequestered.

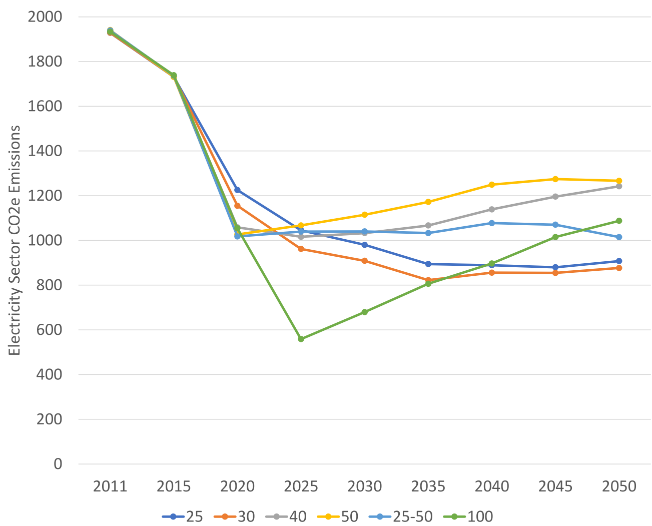

Fig. 14. Electricity sector CO_2e emissions with various CCS tax credit values (Mt).

5.3. *Sectoral policy portfolio scenarios: comparison and policy effectiveness*

We have designed the three sectoral policy portfolio scenarios based on the political feasibility of climate policies. The CCS tax credit plays a critical role in reducing GHG emissions from the electricity sector in the Low Alignment scenario. The PTC/ITC policies enable the deployment of more renewable energy in power generation. The national energy efficiency resource standard leads to a reduction in natural gas consumption in the Medium Alignment scenario, and the clean electricity standard strengthens this reduction in the High Alignment scenario. Coal is never entirely phased out.

In the transportation sector, the ZEV tax credit contributes a significant portion of GHG emissions reductions, as the ZEV mandate in the Medium Alignment scenario only leads to a further 0.4% reduction in transportation sector emissions. The ZEV tax credit actually incentivizes all new LDVs to be EVs starting in 2040, which is only five years later than what the ZEV mandate requires. In the High Alignment scenario, the focus on MDVs and HDVs leads to another 5% decrease in GHG emissions. The ZEV mandate for MDVs and HDVs reduces diesel consumption, which remains high under Low Alignment and Medium Alignment. There are no policies that attempt to reduce overall travel demand and only limited policies that target mode shifting, both of which could play larger roles in reducing transportation GHG emissions (Hankey and Marshall, 2010; McCollum and Yang, 2009).

The buildings sector is less affected by the sectoral policy portfolios, with decarbonization highly reliant on decarbonization in the electricity sector. With no direct policies addressing the industrial sector or the jet fuel consumption of aviation (part of the transportation sector), these segments of the energy system remain close to their baselines in the BAU scenario.

6. Conclusions and policy implications

6.1. *Summary of key findings*

We improve the policy realism of energy system optimization models by incorporating portfolios of granular, sectoral policies into the US-TIMES model. Our sectoral policy portfolios are based on a detailed analysis of the climate policies that would be politically feasible in different political environments. Incorporating these portfolios into an energy system optimization model enables us to assess and compare their technological, economic, and GHG emissions impacts. Relative to most of the energy system modeling literature, which has mainly focused on techno-economic considerations and optimal decarbonization pathways, our work highlights the importance of integrating political feasibility considerations into climate policy modeling to understand how political realities can constrain decarbonization strategies and affect outcomes.

The most cost-effective near-term decarbonization opportunities exist in the electricity sector, which corroborates previous findings from other studies that used the US-TIMES/MARKAL model (Roth et al., 2020; Victor et al., 2018). The electricity sector results highlight the significance of renewables, with renewables accounting for roughly 72% of generation in 2050 in the High Alignment scenario. In our sectoral policy portfolio scenarios, deployment of renewable energy technologies is incentivized by tax credit policies and strengthened by regulations like the clean electricity standard. CCS tax credits, which often draw broad political support, result in CCS technologies playing important roles in the electricity sector; in the High Alignment scenario, up to 87% of all GHG emissions produced by electricity generation in 2050 are captured and sequestered. Transportation can be decarbonized through combinations of more stringent CAFE standards, a ZEV tax credit, and a ZEV mandate (targeting LDVs, MDVs, and HDVs). Buildings sector results confirm the central role of decarbonizing electricity, since reducing GHG emissions in the buildings sector relies heavily on substantial electrification powered by building-integrated renewables (e.g., rooftop solar PV) and growing grid-scale renewable generation.

Lastly, we calculate average abatement costs for the three sectoral policy portfolio scenarios and the System80 scenario relative to BAU. The System80 scenario achieves much greater economy-wide GHG reductions than the sectoral policy portfolios, which requires costly mitigation strategies such as reducing natural gas consumption in the buildings sector, more dramatically reducing diesel consumption in the transportation sector, and most significantly, decarbonizing the industrial sector by substituting electricity for natural gas. Decarbonizing the U.S. economy using portfolios of sectoral policies is several times more costly than doing so via the ideal, least-cost pathways, but the gap between the two AAC values narrows as GHG emissions are reduced more. The reason is that as political enthusiasm for decarbonization increases, a wider range of climate policy instruments become politically viable, and these instruments tend to be more cost-effective than many of the policies that are viable in less favorable political contexts. It is important to note that all AACs we calculate in this study are lower than mainstream SCC estimates. For example, the U.S. Interagency Working Group on Social Cost of Greenhouse Gases (2021) SCC estimates with a 3% discount rate range from \$51/tCO_2e in 2020 to \$85/tCO_2e in 2050, in 2020 dollars. This suggests that even if political considerations mean that the U.S. cannot necessarily follow the most cost-effective pathway to decarbonize the economy, many politically viable climate policy approaches would still likely produce net benefits.

6.2. *Policy implications*

Reaching a deep decarbonization target by 2050 in the U.S. is a challenging goal, especially given political uncertainty. By combining political-organizational and techno-economic considerations for future policy formulation and evaluation, our work can inform policymakers in several ways. First, in the near term, infrastructure transformation is needed to guarantee adequate clean electricity generation to satisfy rapidly growing demand for it stemming from end-use electrification. Second, our work highlights several important sources of GHG emissions that the set of politically feasible policies included in our sectoral policy portfolios would likely struggle to address. New technologies and policies are needed to address emissions from MDVs and HDVs, aviation, and energy-intensive industries. Third, sectoral policies addressing end-use sectors should not be assessed in isolation, as they interact in crucial ways with the electricity sector. Fourth, greater political alignment allows electrification to play an increasingly vital role as a central component of decarbonization since we observe the highest power generation from renewables in the High Alignment scenario. Fifth, as the political environment allows more ambitious climate policies, deeper decarbonization can actually be achieved at a lower average abatement cost because more economically efficient policy instruments become politically feasible.

6.3. Limitations and future research directions

Like most modeling studies, our analysis has limitations. The input data in the EPAUS9rT database are known to be imperfect. Its assumptions are based on the EIA's Annual Energy Outlook (U.S. Energy Information Administration (EIA), 2020), which cannot perfectly project future demands and has historically underestimated technological progress.[6] We modified cost assumptions for key technologies by using the cost estimates from the National Renewable Energy Laboratory's Annual Technology Baseline (National Renewable Energy Laboratory (NREL), 2020), which we deem more plausible, but these assumptions could certainly overestimate or underestimate future technology costs. The model does not explicitly represent important energy infrastructure networks such as electric transmission and distribution, pipelines, and EV charging stations. Being able to model these infrastructures and policies designed to support investments in them would make the model and our policy analysis more comprehensive. As we previously discussed, our AAC calculations do not capture the full costs of some policies that we could only represent in a stylized fashion in US-TIMES. For example, the mass transit and low-carbon mobility policy in the transportation sector is represented as shifting travel demand from LDVs to bus and rail modes; the costs of all these projects undertaken at the urban scale would be very difficult to estimate and we omit them from our calculations. Similarly, our US-TIMES model that represents the entire U.S. in nine large regions cannot properly model promising opportunities to reduce emissions through demand-reducing interventions at finer spatial scales, such as reducing travel demand by altering urban land use patterns or encouraging telecommuting (Hankey and Marshall, 2010; Leibowicz, 2017; Wiedenhofer et al., 2013; Zhu and Leibowicz, 2020). Beyond the model itself, we emphasize that our sectoral policy portfolios are based on a static assessment of current political feasibility. Between now and 2050, the implications of each political context for the feasibility of different climate policy instruments could certainly change.

The application of energy system optimization models is challenging and requires many judgment calls (DeCarolis et al., 2017). Incorporating more granular, sectoral policies only amplifies these challenges. Despite its limitations, our work enhances policy realism in energy system optimization models. In practice, climate change mitigation requires a diverse and complex set of policy efforts. Climate change mitigation research requires the integration of political factors (Nielsen et al., 2020; Peng et al., 2021a,b), and models are ripe for changes to reflect political realities and enable more practically valuable assessments of policy options. By combining the political-organizational and techno-economic dimensions of decarbonization into a single model-based analysis, we hope to inspire future research to investigate mitigation policies and strategies from an interdisciplinary perspective.

CRediT authorship contribution statement

Qianru Zhu: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Benjamin D. Leibowicz:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Joshua W. Busby:** Conceptualization, Methodology, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Sarang Shidore:** Conceptualization, Methodology, Investigation, Writing – review & editing. **David E. Adelman:** Conceptualization, Methodology, Resources, Writing – review & editing, Project administration, Funding acquisition. **Sheila M. Olmstead:** Conceptualization, Methodology, Resources, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Input data and modification

We begin our modeling efforts by evaluating the technical feasibility of decarbonization targets in US-TIMES with the default assumptions in the EPAUS9rT database. Here, technical feasibility refers to whether or not the model is able to identify a pathway that achieves the desired GHG reductions in the specified sectors (no matter its cost). We implement constraints on total system-wide emissions and also on sectoral emissions in the electricity, transportation, buildings (combining residential and commercial), and industrial (combining industrial, refinery, and resource supply) sectors. In each case, we impose a decarbonization target that requires a specified percentage reduction in carbon dioxide equivalent (CO_2e) emissions by 2050 relative to 2010. This is achieved by enforcing upper bounds on annual emissions starting in 2020 and decreasing linearly to the specified target in 2050. We implement system-wide and sectoral decarbonization targets that range from 0% to 100%, in 5% increments. CO_2e emissions include contributions from CO_2, methane (CH_4), and nitrous oxide (N_2O).

Through this experiment, we are able to determine the most ambitious system-wide and sectoral decarbonization targets that are technically feasible given US-TIMES' default assumptions. These highest-technically-feasible decarbonization levels are important benchmarks for assessing the effectiveness of climate policy approaches. Our findings indicate that the most stringent 2050 decarbonization targets that can be achieved in the electricity, transportation, buildings, and industrial sectors, and system-wide across the whole economy, are 95%, 20%, 25%, 5%, and 45%, respectively. Considering that numerous deep decarbonization studies have analyzed much more ambitious GHG reduction pathways, these technical feasibility results highlight some questionable rigidities embedded within US-TIMES and the default EPAUS9rT input database. Upon further investigation of the default model setup, we identify several constraints in the transportation, buildings, and industrial sectors that define minimum and maximum market shares for various technologies and fuels. For example, for the New England region, US-TIMES establishes a minimum fuel mix

[6] For a brief overview of the Annual Energy Outlook and its limitations, see CRS (2020).

share of 24% for diesel in residential space heating, which persists until 2050. Based on our assessment that these constraints are unnecessarily rigid, we eliminate them in developing our own US-TIMES reference scenario (see Appendix B for more details). The EPAUS9rT database also features very conservative assumptions about the costs of key technologies such as solar photovoltaics (PV), batteries, and electric vehicles (EVs). We replace these default cost assumptions with alternative values from the National Renewable Energy Laboratory's 2020 Annual Technology Baseline (National Renewable Energy Laboratory (NREL), 2020), which we deem more plausible.

With selected constraints lifted and cost data adjusted, we reevaluate the technical feasibility of varying decarbonization targets for each sector and for the whole system, finding that the most ambitious, feasible 2050 GHG reduction targets for electricity, transportation, buildings, industry, and system-wide are 95%, 75%, 80%, 60%, and 80%, respectively.

Appendix B. Creation of the modified reference scenario

The changes that we incorporate into the default US-TIMES model to arrive at our modified reference scenario are to: (1) eliminate the market share constraints for all technologies and fuels in the buildings, industrial, and transportation sectors; (2) modify the investment costs for renewable electricity generation technologies (wind and solar); (3) modify the investment costs for electric LDVs. Our parameter changes for (2) and (3) are based on NREL's Annual Technology Baseline (ATB) (National Renewable Energy Laboratory (NREL), 2020). There are three trajectories for cost estimates in both sectors, and we always use the moderate/mild trajectories. We obtain the ratios of projected investment costs in future years to the investment costs in 2020 (base year) from the ATB, and then apply these ratios (listed in Table B.1) to modify the investment costs of all technology options in these categories in the EPAUS9rT input database for US-TIMES.

Table B.1
Ratios applied to modify default investment cost assumptions.

	2025	2030	2035	2040	2045	2050
Solar PV	0.81	0.62	0.59	0.56	0.54	0.51
Centralized thermal solar	0.81	0.69	0.63	0.59	0.57	0.56
Offshore wind	0.73	0.56	0.47	0.43	0.41	0.37
Onshore wind	0.90	0.79	0.75	0.72	0.68	0.64
100 & 200 mile range EV	0.92	0.83	0.81	0.78	0.75	0.72
300 mile range EV	0.88	0.77	0.75	0.72	0.69	0.66

Appendix C. Details of policies included in the sectoral policy portfolios

- RD&D in clean energy innovation:

Delay retirement of nuclear power plant in R6 (East South Central) from 2035. This is the only region that still has nuclear capacity in 2050; the current database assumes all nuclear retirement in all the other regions by 2050.

- PTC:
  - Model a tax credit of 1.2 cents/kWh for electricity generated from landfill gas, municipal solid waste resources, hydropower;
  - Model a tax credit of 2.3 cents/kWh for electricity generated from wind.
- CCS tax credit extension/enhancement:
  - Implement a $30/ton CO2 sequestered tax credit.
  - There are different types of CCS technologies in the database, including post-combustion capture (coal, natural gas) and pre-combustion capture (central current hydrogen coal/natural gas with CCS), and CO2 capture retrofits.
- Tougher fuel economy standard (regulatory):
  - For new vehicle standards, use the 36.8 mpg as 2020, consistent with what EPA used for 2020. Then use the Obama administration's standard (an increase of 5% every year) to get values for 2025 and 2030. For years beyond 2030, the values remains the same as 2030.
  - In terms of the estimated mpg for all vehicles, we kept the new vehicle mpg/all vehicle mpg ratio EPA used and generated the mpg for all vehicles. The RHS for the constraints is the mpg of all vehicles multiplied by the demand (in bn-vmt).
- ZEV Standard for federal fleets (regulatory):

Use the proportion of electric vehicles in LDV in the BAU scenario, assume that there is an increase of 10% in federal fleets (all ZEV) vehicles each year (starting 2020).

- Mass transit and low-carbon mobility:

Model the demand shift of 15% from LDV to HDV (transit bus and rail passenger) from 2030 to 2050.

- ZEV tax credit extension/enhancement:

Assume that the annual miles traveled by ZEV is 5000 miles and implement an average of $4000 tax credit for purchasing one ZEV. (There is one policy mentioned in the policy paper that there is a 20% tax credit with up to $5000 for ZEV purchase.)

- Model building performance standards, enhanced appliance standards, sustainable home construction and retrofits, Weatherization Assistance Program enhancement, Enhancing efficiency of federal buildings, smart city investments:

  - For Low and Medium Alignment, enhance electric powered-technologies by 25% and reduced demand for space heating and cooling for 17% relative to BAU;
  - For High Alignment, enhance electric powered-technologies by 25% and reduced demand for space heating and cooling for 29% relative to BAU.
- Solar ITC extension:
  - Residential: 26% tax credit for systems installed in 2020 and 22% for systems installed after (including) 2025.
  - Commercial: 26% tax credit for systems installed in 2020 and 10% for systems installed after (including) 2025.
- Tax credits for home electrification

$500 for newly-installed heat pumps (assume the heat pump uses 1.2×10^5 kWh per year)

- National energy efficiency resource standard:

Based on the BAU case, calculate the percentages of natural gas (2020 to 2050), impose upper bounds for the share from natural gas (1% reduction per year in natural gas consumption).

- Carbon price (tax or cap-and-trade):

Implement a $\$20/tCO_2e$ in the electricity sector.

- ZEV Mandate:
  - A national ZEV mandate for LDVs starting 2035 in Medium Alignment.
  - A national ZEV mandate for HDVs starting 2045 in High Alignment.
- Federal clean electricity standard:

Implement a 96.7% CO_2e reduction (since in the reference case we run, the power sector can be decarbonized by 96.7% and does not encounter infeasibility).

- Pollution tax on fossil vehicles:

Implement annual tax for SUVs and assume that annual travel beyond 15,000 miles (about 17%) is to be taxed.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112754.

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