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Decomposing supply-side and demand-side mitigation responses for liquid fuels in energy transition scenarios

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Abstract

The combustion of liquid fuels accounts for a substantial share of total CO_2 emissions in most regions. In energy transition scenarios, emissions from liquid fuels are reduced through a combination of mitigation pathways, including demand-side measures such as greater energy efficiency and electrification, as well as supply-side measures such as deployment of low-carbon fuels and carbon dioxide removal (CDR). However, in published studies, it is difficult to decompose mitigation into contributions from these different pathways or determine which factors may drive scenarios to rely on certain pathways over others. In this study, we develop a set of scenarios using an established global integrated assessment model (GCAM) to span a range of outcomes observed in the literature and apply a decomposition approach to attribute emissions reduction to various pathways. We find that supply-side measures, including low-carbon feedstocks and fuels, along with CDR, account for over 70% of the total emissions reduction from liquid fuels and over 50% of the reduction from liquid fuels used in transportation at the time of net-zero CO_2 emissions. Across mitigation scenarios examined, overall fuel use declines, but the fuels share of total energy system value is relatively stable. Our results can be used to inform discussions about the roles of supply-side and demand-side measures in reducing emissions from fuels.

1. Introduction

Liquid and gaseous hydrocarbon fuels play critical roles in the global economy, providing 52% of global primary energy (341 EJ) and 55% of final energy (247 EJ) in 2024.[1] While long-term energy scenarios consistent with international climate goals entail a shift toward low-carbon electricity and end-use electrification[2], liquid and gaseous hydrocarbon fuels (here referred to collectively as "fuels") continue to provide a substantial share of final energy in most mitigation scenarios.[3, 4] For example, the 2075 projected median amount of final energy from gas and liquids is 74 EJ and 100 EJ, respectively, for scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) with a >50% chance of limiting warming to 2°C (C4 scenarios)[5] in the AR6 database.[6] Even in the most stringent (C1) scenarios that limit warming to 1.5°C, about a third of final energy is from these fuels at midcentury, when net-zero emissions are approximately attained (see Table S3). If fuels remain at the time of net-zero emissions, then a key question is how the emissions associated with those fuels would be mitigated.

There are multiple options for mitigating emissions from fuels: (1) end users could switch toward lower emitting fuels or carriers and/or reduce energy demand; (2) the net carbon intensity of fuels could be reduced by using biogenic or atmospheric carbon (collectively, "carbon neutral") feedstocks; (3) emissions generated during fuel production and use could be reduced by carbon capture and sequestration (CCS); and/or (4) remaining emissions from fuels could be offset by carbon dioxide removal (CDR). CDR could come from another sector, such as bioenergy with CCS (BECCS) in the power sector or from direct air capture with carbon capture and sequestration (DACCS). Alternatively, CDR could come from the fuels production sector by applying CCS to biofuels production, which would sequester biogenic carbon and potentially yield a carbon-negative fuel. While these strategies are known, their relative contributions to emissions reductions within mitigation scenarios and their drivers are less clear.

Several studies have shown that fuels produced with carbon neutral feedstocks, particularly biofuels, are more competitive under climate change mitigation and that their competitiveness grows with higher mitigation ambition.[7, 8, 9] Fuels synthesized from hydrogen (H_2) and captured atmospheric carbon (here referred to as "synthetic fuels") also become more competitive when biomass and/or geologic sequestration are constrained in decarbonization scenarios.[8, 9, 10, 11, 12] Biofuels, synthetic fuels, and fossil fuels coupled with CDR each emerge as dominant options for reducing emissions from remaining fuels under different assumptions about these constraints.[11, 12]While these studies incorporated the role of end use electrification when specifying future fuel demands, they did not endogenously represent how demand might be affected by increasing production costs—and therefore prices—of fuels. By estimating fuels demand endogenously in this study, we can examine the relative contributions from demand-side and supply-side emissions reductions.

While other scenarios assessed by the IPCC and other studies estimate fuels demand endogenously, the available literature does not clearly indicate the relative roles for supply-side and demand-side mitigation measures.[13, 14] Moreover, when mitigation is decomposed for different sectors (e.g., passenger[15] and freight transportation[16], chemicals[17], and the broader energy system[18]), the categorization used by these studies often obscures the relative contributions from supply-side and demand-side mitigation. For example, Hoehne et al. (2025) show emissions mitigation for "Supply: Liquids + Other", but the mitigation associated with feed switching was reported in "Demand: Transportation," while some of the mitigation from biofuels with CCS would presumably be included in the "CDR" category.[19] This particular categorization and other similar approaches are useful for some purposes, but they do not help to clarify the roles of demand-side measures such as electrification and supply-side measures such as feed switching in reducing fuels-related emissions.

In this study, we use the Global Change Analysis Model (GCAM)[20], a state-of-the-art open-source integrated assessment model (IAM), to decompose how emissions from liquid fuels are mitigated

in global scenarios that attain specific climate objectives. GCAM is well suited for this analysis, given its global coverage, ability to project over longer time horizons, and its representation of the main demand-side and supply-side emissions mitigation pathways for fuels. Across a range of scenarios, we find that reducing the carbon intensity of liquid fuels and deployment of CDR generally contribute more emissions reduction than switching fuels or energy carriers consumed by end users in the long run. While liquid fuel demand is responsive to prices, which increase as resource constraints are tightened, these responses do not substantially change the emissions decomposition. Rather, resource assumptions primarily determine the balance between fuel carbon intensity reductions and CDR deployment, with the share of demand-side mitigation less affected by these assumptions. Finally, we find that while the use of fuels decreases as constraints on the energy system are tightened, the value share of fuels is relatively stable, suggesting that the sources of energy system value in transition scenarios may be relatively robust to assumptions about demand and resources. Together these results provide additional insights about the roles of different energy sectors and products in the energy transition.

2. Results

2.1. Drivers of energy system outcomes

Figure 1 shows balances for key energy vectors and captured CO_2 for the GCAM scenarios in 2075, the year in which energy and industrial CO_2 emissions reach net zero in the emissions reduction cases (see Methods for descriptions of the GCAM scenarios). In the emissions reduction cases, demand for gas and liquid fuels decreases, with liquids decreasing by 16% to 43% (panel C) and gas decreasing by 21% to 76% (panel D) relative to 2021. The variation in gas is greater because the availability of CO_2 storage affects the competitiveness of natural gas with CCS, particularly in the power sector. More fossil liquids also remain in the scenarios with higher CO_2 storage because of the availability of CDR. In the HS_HB scenario, emissions from remaining fossil fuels tend to be offset with BECCS, whereas in the HS_LB case, emissions from remaining fossil fuels tend to be offset by DAC (panel F).

When sequestration is limited, fewer remaining emissions can be offset with CDR, which leads to an increase in alternative fuels production, primarily bioliquids in the LS_HB scenario (40% of liquids) and a mix of bioliquids and synthetic liquids in the LS_LB scenario (44% of liquids). While biomass and captured atmospheric carbon feedstocks together account for 28-53% of liquids production in the low sequestration scenarios, neither feedstock is substantially used in the production of gas in any of our cases (together representing 1-6% of gas production). Deployment of alternative production routes for liquids rather than gas reflects the fact that natural gas is cheaper than oil in most regions over the projection period, so displacing natural gas is more costly.

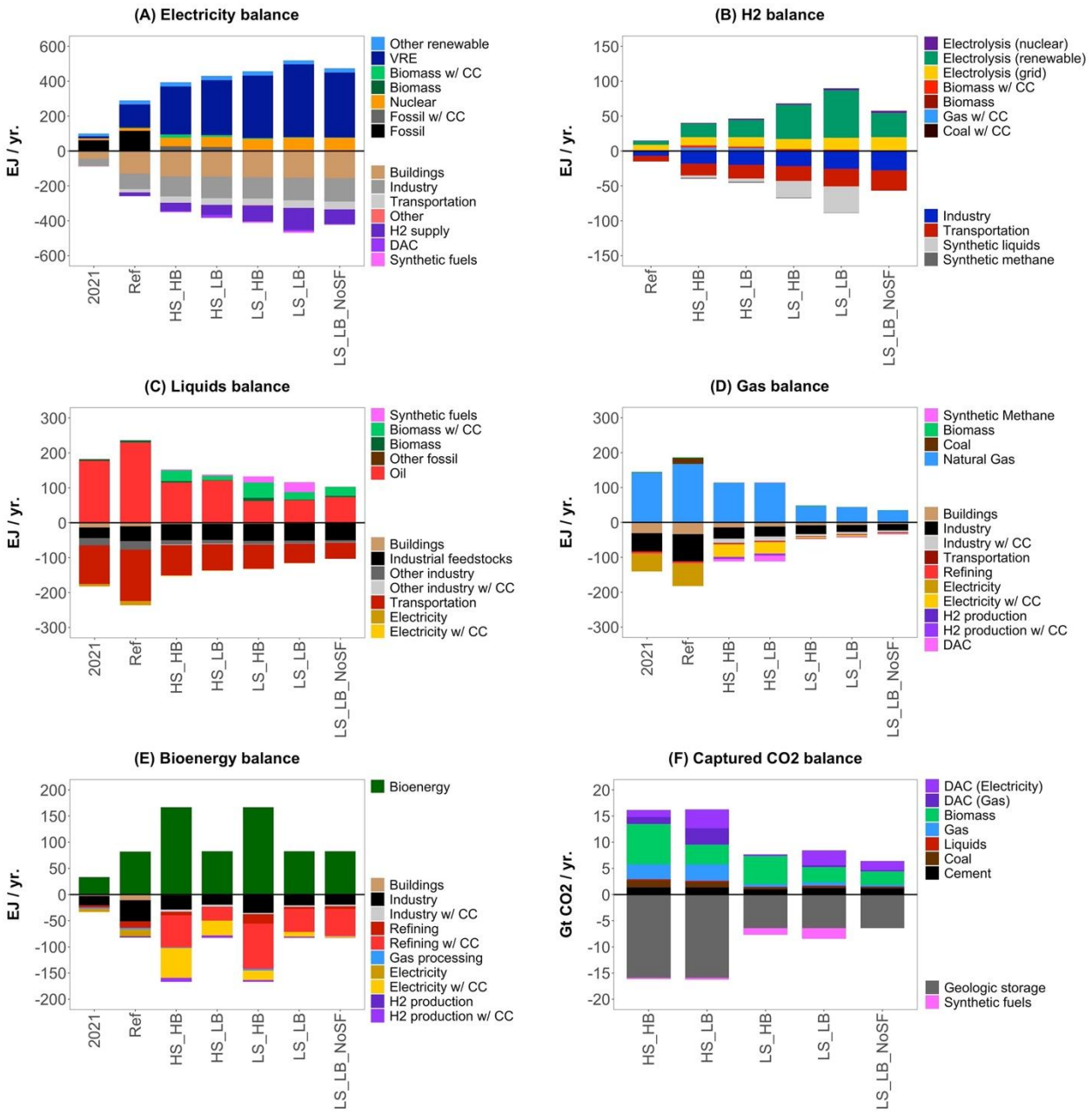


Figure 1. Global energy system balance in 2021 and 2075. Positive values correspond to production and negative values correspond to consumption. "CC" refers to carbon capture. Electricity represents gross generation and does not include industrial cogeneration. Electricity and hydrogen demand do not include losses, and gas consumed within pipelines for compression is not included in the demand portion of the bars. Gas balances also do not include natural gas utilized during unconventional oil upgrading.

The production of liquid fuels decreases as resource constraints are tightened, because higher costs lead to higher prices, which lowers demand. Liquid fuel demand decreases by 35% to 56% relative to the Reference (Ref) in the emissions reduction cases. The largest decrease in demand for fuels occurs when sequestration and bioenergy are jointly limited in conjunction with the inability to produce synthetic fuels (LS_LB_NoSF; panels C and D), leading to an energy system with higher end-use electrification (59% of final energy, compared to 49-57% in the other emissions reduction cases). End-use demand for hydrogen (H_2) is also largest in this scenario (57 EJ; panel B), as H_2 complements electrification by providing energy that is no longer supplied by hydrocarbon fuels and may be less suited to electrification. On the other hand, overall electricity and H_2 demand are the largest in the LS_LB case because H_2 is used as a feedstock for synthetic fuels (43% of hydrogen demand), with almost all hydrogen produced electrolytically in this case such that hydrogen supply accounts for 26% of electricity consumption.

Additionally, we find that the sectoral demand for bioenergy is strongly determined by the availability of carbon sequestration (panel E). While biomass is mostly coupled with CCS to provide CDR in emissions reduction scenarios, its disposition changes as constraints are varied. In the least constrained case (HS_HB), BECCS is deployed evenly between electricity and liquid fuels production (34% and 37% of bioenergy demand, respectively). However, as constraints on sequestration are tightened, BECCS is preferentially deployed in liquids production (e.g., 53% of bioenergy demand in the LS_LB scenario). This tendency occurs because tighter constraints on sequestration disadvantage technologies that produce more CO_2 per unit of useful energy. Biofuels with CCS produce less CO_2 per unit of useful energy (compared to BECCS in electricity) because the conversion efficiency from biomass to energy is assumed to be higher and because more of the carbon winds up in the product that is mostly later combusted.

The qualitative findings above are largely consistent with other studies.[11, 12] While a comprehensive comparison is not possible, we place GCAM results in context by comparing outcomes to those from the IPCC AR6 scenario database.[6] Figures S1-S3 compare liquids production and final energy in the GCAM emissions reduction scenarios to those outcomes in the database for the scenarios with comparable emissions stringency (Figure S4). As seen in the figures, results from our GCAM emissions reduction scenarios generally fall within the range of the IPCC database scenarios, often spanning a large amount of the variation in those scenarios. It is worth noting that the AR6 database does not include a reporting category for synthetic liquid fuels. In addition, the number of scenarios reported for each category varies, and the database does not necessarily span the range of all IAM scenarios. Nevertheless, these comparisons suggest that the mechanisms governing how emissions from fuels are mitigated in GCAM are plausible drivers in other IAMs as well.

2.2. Decomposing supply-side and demand-side mitigation

Panel A of Figure 2 shows a decomposition of emissions mitigation for the emissions reduction scenarios relative to the Reference case in 2075. We further decompose emissions mitigation for hydrocarbon fuels into demand and decarbonization effects, with the former representing emissions abated by reduced demand and the latter reflecting the reduction in carbon intensity, which could be attained by changing feeds (which lowers the net carbon content of fuels) or sequestering carbon during energy production or use (e.g., carbon embodied within a product or sequestered geologically; see Methods section 4.3). While the power sector provides a large and stable source of mitigation across the scenarios (19-23 Gt CO_2), the size and composition of emissions reductions vary for hydrocarbon fuels (panel A).

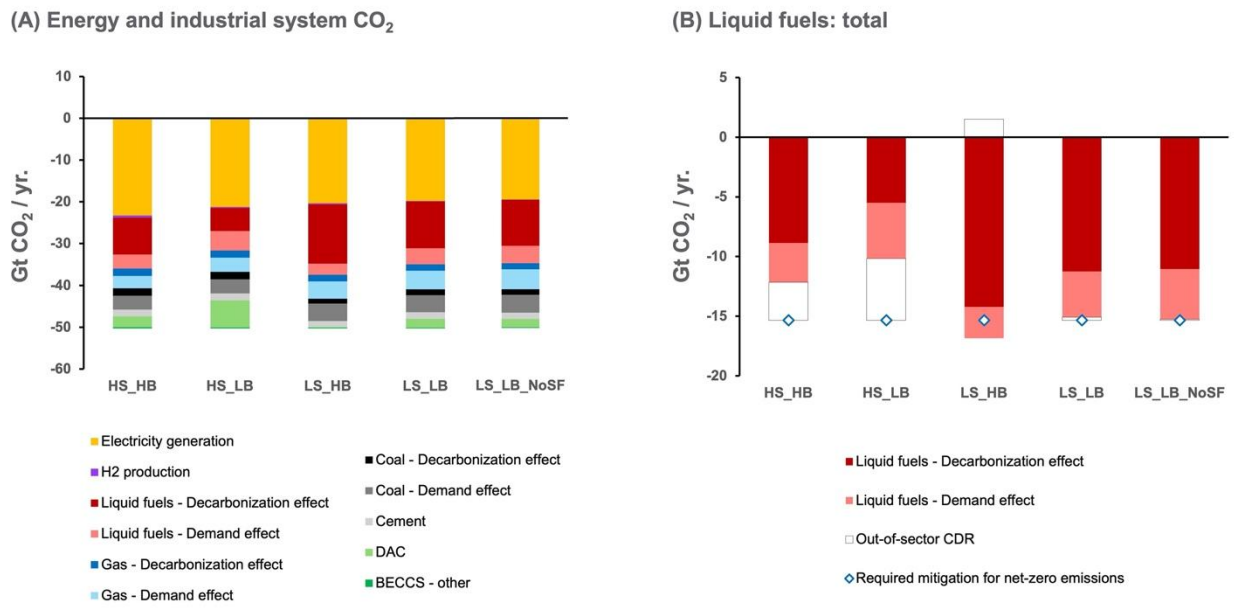
The reduction in emissions from liquid fuels is largest in scenarios in which sequestration is limited (15-17 Gt CO_2), as there is less ability to offset unabated fuel combustion emissions with CDR.

The reduction is smallest for liquid fuels in the HS_LB scenario (10 Gt CO_2), as more conventional liquid fuels remain in the energy system (121 EJ), with emissions primarily offset by DAC. This scenario is also the only case in which the demand effect is similar in size to the decarbonization effect, but this is driven more by the availability of removals outside of the fuels sector (DAC) than by the size of the demand response. On the other hand, there is less variation in total mitigation from coal and gas (5.1-5.6 and 4.8-6.2 Gt CO_2, respectively), with their demand effects exceeding their decarbonization effects across all cases. The mitigation contributions for coal and gas used in sectors in which they can be coupled with CCS (power, hydrogen) are reported in those consuming sectors. The mitigation explicitly reported for coal and gas in Panel A occurs in end-use sectors in which fuel switching is cost-effective, reducing the demand for these fuels.

Panels B and C further decompose the relative mitigation response for liquid fuels. The total mitigation required to fully mitigate the emissions from liquid fuels (including the emissions from the combustion of those fuels) is equal to their emissions in the Reference case. Therefore, when the demand and decarbonization effects together fall short of this amount, the difference can be used to infer the CDR from other sectors ("Out-of-sector CDR") that would be required for liquid fuels to attain net-zero emissions. When the demand and decarbonization effects exceed the amount required to attain net-zero emissions, the difference could be interpreted as excess removals sold to other sectors (shown as positive "Out-of-sector CDR" in panel B).

In cases with high sequestration, we find that 70-79% of the mitigation required for liquid fuels to reach net-zero emissions is from the combination of liquids decarbonization and CDR purchases, with a substantial share coming from CDR purchases (21-34%). In the low sequestration cases, in which most of the CDR occurs during liquids production and use, including when biogenic or atmospheric carbon is embodied within chemical products, a similar share (73-83%) of the mitigation required to reach net-zero emissions is from liquids decarbonization and CDR, but with a smaller contribution from CDR (2% in LS_LB) or an opportunity to sell CDR credits (in LS_HB). Across the cases, the demand effect accounts for 17-30% of the total mitigation required for liquids production to reach net-zero emissions. At midcentury, well before the net-zero emissions year, the demand effect is considerably higher, but the decarbonization effect is still larger in three scenarios (Tables S5-S7).

Panel C of Figure 2 further decomposes emissions mitigation for liquid fuels for transportation and non-transportation uses. In contrast to the decomposition for total liquids (panel B), the demand effect is the largest contributor to mitigation for liquids used in the transportation sector for the three low bioenergy scenarios (43-49%). More constrained scenarios lead to higher liquid fuel prices, which drive more demand-side substitution in transportation. However, the combination of decarbonization and CDR purchases still accounts for more than half (51-69%) of the mitigation within transportation for all scenarios. In contrast, in non-transportation uses, the decarbonization effect dominates, with relatively small demand-side changes, as there are fewer substitution possibilities when using liquids as industrial feedstocks (since feed switching between fossil and non-fossil feeds is represented within liquids production rather than in the chemicals sector in GCAM). Given that emissions may also be sequestered in the final product, the decarbonization contribution often exceeds the mitigation necessary to attain net-zero emissions in non-transportation uses (e.g., chemicals), which creates an opportunity to sell CDR to other sectors.



(C) Liquid fuels: relative mitigation contribution

Sector	Effect	Scenario				
		HS_HB	HS_LB	LS_HB	LS_LB	LS_LB_NoSF
Total	Decarbonization	58%	36%	93%	73%	72%
	Demand	21%	30%	17%	25%	27%
	Out-of-sector CDR	21%	34%	-10%	2%	0%
Transportation	Decarbonization	37%	18%	60%	41%	37%
	Demand	32%	43%	31%	44%	49%
	Out-of-sector CDR	32%	39%	9%	15%	13%
Non-transportation	Decarbonization	114%	75%	180%	145%	143%
	Demand	6%	12%	0%	4%	5%
	Out-of-sector CDR	-20%	13%	-80%	-49%	-47%

Figure 2. Global energy and industrial system emissions mitigation by source in 2075. Emissions reductions are shown relative to the Reference ("Ref") scenario. Panel A decomposes all energy system emissions, Panel B decomposes all liquid fuel emissions, and Panel C further decomposes liquids used in transportation and non-transportation applications. In Panel A, hydrocarbon categories do not include emissions associated with their use during the production of other sources of secondary energy (e.g., electricity), as those emissions appear in the secondary energy sector. Removals from BECCS are included within secondary energy sectors, except for "BECCS – other", which includes BECCS in final energy applications. Cement includes emissions from limestone calcination but does not include emissions from process heat, because those emissions are reported with the relevant fuel. "CDR" refers to carbon dioxide removal. Relative mitigation contributions reported in panel (C) may not sum to 100% due to rounding. See Methods section 4.3 for more information on how emissions mitigation was decomposed.

2.3. Aggregate energy system scale, composition, and value

Bioenergy and geologic sequestration availability not only drive differences in energy system pathways and fuels mitigation but also affect the size and composition of the global energy system. For example, as shown in Panel A of Figure 3, total primary energy in emissions reduction scenarios decreases relative to the Reference scenario (-137 to -256 EJ), with tighter constraints driving greater reductions, as fossil primary energy roughly scales with CDR in those scenarios. Substituting fossil primary energy for other primary energy tends to decrease total primary energy because non-fossil

primary energy is reported in direct equivalent units. Final energy is also reduced relative to the Reference case (-85 to -133 EJ) as shown in Panel B (see Figures S5-S7 for final energy and service output by end-use sector). Here the more constrained cases have lower service demand (due to higher prices) but also more electricity as hydrocarbon fuels are increasingly more expensive. Electrification tends to reduce final energy even without changes in service demand because some electric technologies are more energy efficient.

Secondary energy provides another indicator of scale. Secondary energy effectively represents the amount of useful energy that is produced, whether it is delivered to final end users or used to produce other forms of energy. When all secondary energy is delivered to final energy consumption, then secondary energy would resemble final energy (with differences due to delivery losses). However, when secondary energy is used to make other useful forms of energy (e.g., natural gas used to make electricity, electricity used to make hydrogen, or hydrogen used to make liquid fuels) then secondary energy will further increase relative to final energy (Figure S8).

Total secondary energy is relatively insensitive to the resource constraints (panel C), as more constrained cases tend to have more sector coupling, and thus more electricity and hydrogen that counteracts the greater reduction in hydrocarbon fuels in these cases. The most coupling occurs in the LS_LB case in which electricity and hydrogen are used to make a substantial amount of liquid fuel. While the scale of secondary energy is relatively stable across the cases, panel E shows that the composition of secondary energy changes, with electricity accounting for a larger share of total secondary energy as constraints are tightened.

Panels D and F show secondary energy value, which can be compared to panels C and E. While secondary energy represents the amount of energy produced, secondary energy value represents the revenue associated with selling that energy. Value is estimated as the product of each source of secondary energy that is sold and the price of that energy. Prices reflect the carbon price penalty on emitting sources (see Table S4 for carbon prices). Value is not a measure of profitability, as it does not account for costs, but it can be used as another metric to understand how the roles of specific technologies, sectors, or sources of energy may change in the future.[21]

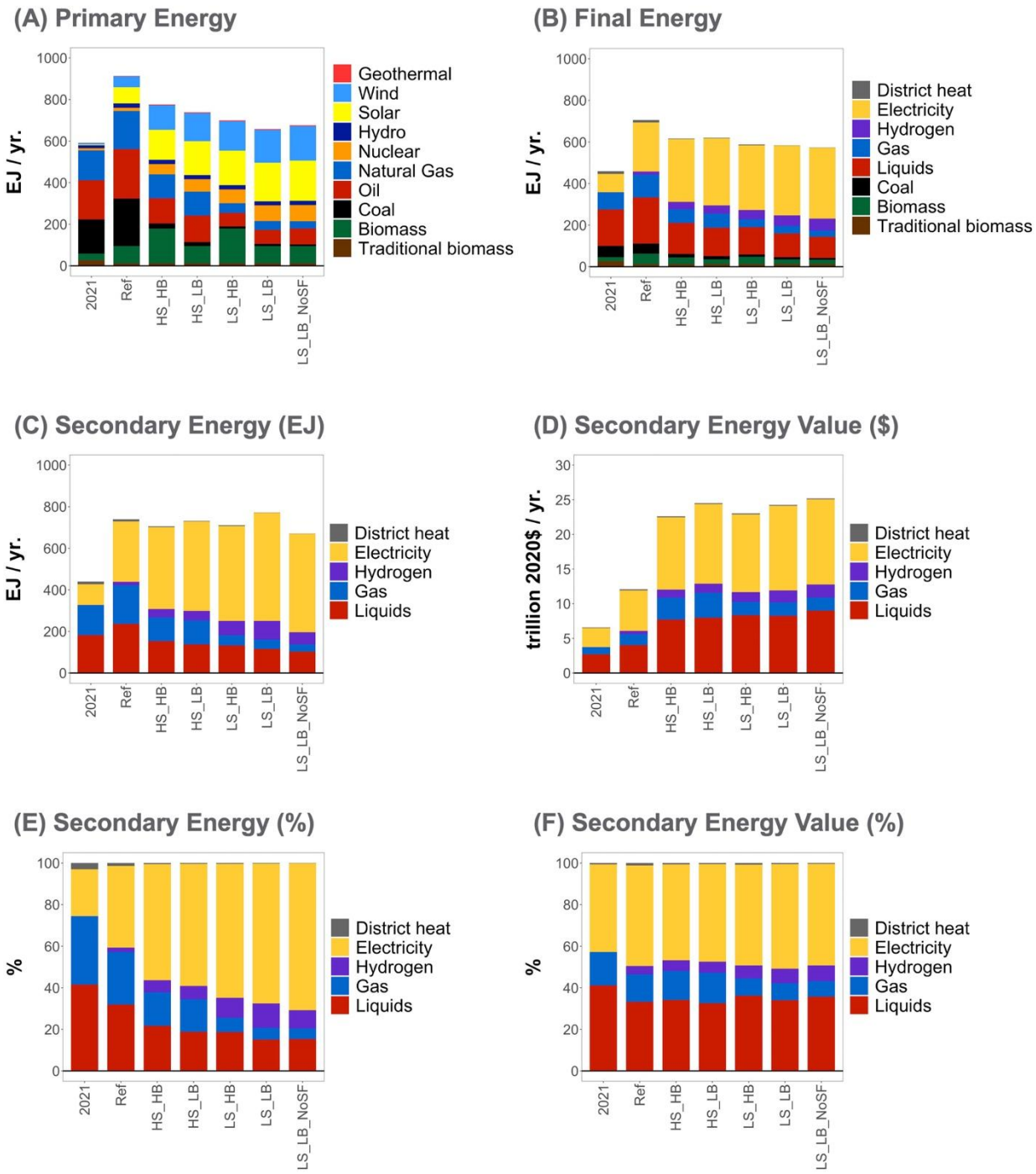


Figure 3. Global energy system scale by energy type and source in 2021 and 2075. Primary energy is reported in direct equivalent units (panel A). Secondary energy (panels C and E) does not include industrial cogeneration. Secondary energy value for each sector (panels D and F) only includes revenues from marketed primary products sold by that sector (i.e., it does not include hydrogen produced and consumed onsite for stationary industrial applications or fuel synthesis). The secondary energy prices used to estimate value include the associated carbon tax on emitting sources.

Because total value increases in cases in which carbon is priced (panel D), value share may be a more useful metric for understanding differences between cases (panel F). Comparing panels E and F we

find that, while electricity accounts for a larger share of secondary energy as constraints are tightened, it accounts for about the same share of value (46-50% in the emissions reduction cases). On the other hand, fuels account for a smaller share of secondary energy as constraints are tightened, but also about the same share of value (42-48%). This suggests that, in decarbonization scenarios, market volumes and prices are inversely related. As more electricity is sold, its price increases less rapidly than fuels, and as fuels production decreases, fuel prices increase more rapidly than electricity (relative to 2021; see SI Figure S9). While price changes may depend, in part, on the policy instrument used to drive emissions reduction, they will more fundamentally depend on the difference in abatement costs between sectors. In any case, these results provide different ways to view the roles and contributions of different energy sectors and products in an energy transition.

3. Discussion

This study sheds light on how emissions from liquid fuels are reduced in energy transition scenarios. While such scenarios typically rely on a combination of mitigation measures—end-use fuel switching and demand reduction, deployment of low-carbon fuels, coupling fuel production and use with CCS, and CDR—the relative contribution from each of these measures is less clear. Most commonly, studies report changes in direct transportation emissions, thereby combining the contributions from end-use measures and low-carbon fuels. To clarify these contributions, we first developed several illustrative scenarios, varying assumptions about bioenergy and CO_2 storage availability, given the roles of these resources in enabling or constraining low-carbon fuels and CDR. We then employed a decomposition approach to separate the contributions from end-use measures and low-carbon fuels and separately inferred the contribution from out-of-sector CDR.

When all liquid fuels are considered together, regardless of whether they are used as transportation fuels or as industrial feedstocks, we find that the decarbonization effect—the carbon intensity (CI) reduction of the fuels themselves, inclusive of CCS used in conjunction with fuels production and use—provides the largest source of mitigation in most scenarios. One notable exception is the HS_LB case in which DACCS provides an offset, limiting the CI reduction of the fuel itself. In this scenario the decarbonization effect is still the largest source of mitigation (36%), but out-of-sector CDR is comparable (34%). The out-of-sector CDR share is substantial in the scenarios with higher sequestration, while it is small or negative in the scenarios with low sequestration. A negative share for the out-of-sector CDR term means that liquids production and use would have net-negative emissions at the time of net-zero energy system emissions.

For liquid fuels outside of the transportation sector, the decarbonization effect is larger than the demand effect in all scenarios, as end-use substitution opportunities available to transportation are not as readily available for such applications (e.g., chemical feedstocks). In some cases, the extent of CI reduction is sufficient to drive net-negative emissions, which would enable these sectors to sell CDR to other sectors. It should be noted, however, that emissions from process heat used to make chemicals are attributed to the fuels used to generate that heat. For fuels allocated to the transportation sector, the contributions from different mitigation measures vary more between scenarios. The demand contribution is relatively stable but never more than half of total mitigation at the time of net-zero emissions (Figure 2 panel C). The remaining contributions are split between fuel CI reductions and out-of-sector-CDR, both of which could be in scope for sectoral policies placed on fuels, such as low-carbon fuels standards. Among these, the CDR contribution is highest in the scenarios with more geologic sequestration availability, whereas the fuel CI contribution is highest in the scenarios with less sequestration availability.

These results have implications for both policy development and research on energy transition scenarios. On scenarios, our results confirm several findings from the energy systems and integrated

assessment modeling literature. First, we find that assumptions about bioenergy and CO_2 sequestration drive substantial differences in how emissions from liquid fuels are mitigated. Second, bioenergy is increasingly used for liquids production (BECCS in liquids) rather than for electricity production (BECCS in power) as the sequestration constraint is tightened. Third, while electricity production expands in all scenarios, the increase in hydrogen production depends in part on how much is used as a feedstock for hydrocarbon fuels. Fourth, it is typically more cost-effective to reduce the carbon intensity of liquids than to do so for gas, meaning that remaining emissions from gas are mitigated by applying CCS where it is combusted, or the emissions are offset using CDR. While other energy system modeling studies have made similar observations[11, 12], our study replicates these outcomes in a model that includes endogenous demand-side responses to changes in realized fuel prices resulting from how fuels are produced.

On policy, our results suggest that a substantial share of emissions from liquid fuels could be mitigated using approaches that reduce the carbon intensity of fuels if biofuels with CCS are enabled by such policies. The opportunity to deploy fuels with net-negative carbon intensities becomes a substantial mitigation lever. Demand-side measures are also important, but their contribution to mitigation is limited by several factors. One is that some demand-side changes—such as vehicle electrification— occur in the Reference case (Figure S7). Some end-use technological choices are not as heavily affected by carbon pricing as by other factors, such as vehicle costs and consumer preferences. Another is that some transportation sectors, including some that are growing—such as aviation—are less likely to electrify. Only about a third of final transportation energy is from LDV in 2075 in our emissions reduction scenarios. In addition, as the carbon intensity of liquid fuels is reduced, switching from those fuels to electricity results in less emissions reduction. Overall, our results suggest that balancing supply-side and demand-side measures would facilitate cost-effective mitigation more than either approach on its own.

These findings are also relevant to how modeling is used to inform policy. As discussed earlier, supply-side and demand-side mitigation is often conflated when transportation emissions are reported as a single category. When supply-side categories—such as refining—are shown, the relatively small amount of mitigation that occurs from reducing direct emissions at refineries may suggest to users of this information that there is relatively little that can be done to reduce emissions from fuels. To avoid misinterpretation, additional reporting that clarifies the relative contributions from fuel CI reductions could be considered. Although it is not possible to apply the decomposition from this paper to scenarios assessed by the IPCC, comparisons of key outcomes from this study to those scenarios suggest that the qualitative findings from this paper would apply to many mitigation scenarios assessed by the IPCC.

Lastly, our results suggest several opportunities for future work. Greater comparison of transition pathways focusing on the evolution of hydrocarbon fuels production would be informative for decision-makers given that a substantial share of final energy typically comes from such fuels even at the time of net-zero emissions. Progress in this area will likely require not only attention from system models but also greater emphasis on the connections between techno-economic assessment, process modeling, and system modeling. More focus on the chemicals sector would also be relevant given the connections between fuels and chemicals production. A deeper focus on the pathways by which natural gas emissions are reduced would also be informative. Finally, given that emissions from fuels are not covered in many currently operating emissions trading systems, exploring differences between policy instruments that address these emissions, such as low-carbon fuels standards, among others, could inform the evolution of emissions reduction policies in multiple regions.

4. Methods

4.1. Global Change Analysis Model (GCAM)

GCAM version 8.6[20] was used for this study. GCAM is an open-source integrated assessment model (IAM) with global coverage that runs recursively in five-year timesteps through 2100 and links the energy, land, water, and climate systems with the economy.[20] GCAM has 32 energy-economic regions, with historical energy production and demand calibrated to the International Energy Agency's (IEA) 2023 World Energy Balances.[22, 23, 24] Within each region and future model period, energy service demands are driven by population and income, with additional assumptions about service demand elasticity. Here, socio-economic assumptions for each region are based on the 'middle-of-the-road' Shared Socioeconomic Pathway 2 (SSP2).[25] Alternative technologies within each sector and region compete on a levelized cost basis to supply each service using a logit choice formulation,[26] with exogenous assumptions about technology costs and performance. Costs may also include a carbon penalty (or subsidy) on CO_2 emissions (or removals) depending on the emissions reduction policies assumed. For this study, GCAM version 8.6[20] was modified to include liquid and gas fuels that are synthesized from captured carbon of atmospheric origin from any energy or industrial source and hydrogen (i.e., "synthetic fuels"). These modifications, as well as additional methodological details, are provided in Supporting Information section S.1.

4.2. Global energy transition scenarios

Six scenarios were specified by varying four assumptions (Table 1). The first case is a counterfactual Reference scenario ("Ref"). The five remaining scenarios are CO_2 emissions reductions cases with emissions limits on global energy and industrial CO_2 emissions linearly interpolated from 40 Gt in 2025 to net-zero emissions in 2075 (Figure S4). A globally uniform carbon price is endogenously computed and applied to energy and industrial CO_2 emissions in order achieve this emissions trajectory. A fraction of the energy and industrial system carbon price, reaching 50% by 2050, is applied to land use change emissions using GCAM's default approach. The terrestrial carbon price mitigates excessive deforestation for bioenergy production and induces additional mitigation through afforestation and reforestation.

Four emissions reduction scenarios are constructed by varying the amount of global geologic CO_2 sequestration and modern primary bioenergy available, including both a high ("HS" and "HB") and low ("LS" and "LB") set of assumptions. The high and low set of assumptions linearly interpolate from the 2025 model projections to the 90^{th} and 10^{th} percentiles, respectively, of the C4 scenarios in 2100 from the IPCC AR6 database.[6] The C4 scenarios limit warming to 2°C through the century with a >50% likelihood, exclusive of the more stringent C1-C3 eligible scenarios.[5] The 2100 constraint values are shown in Table 1, with the low bioenergy terminal value similar to the estimate of Creutzig et al. (2015) for "sustainable technical [bioenergy] potential" (high agreement: 100 EJ per year)[27] that has been used in previous modeling studies.[28, 29] The exogenous geologic CO_2 sequestration and bioenergy constraint values for each model period are provided in Table S2. Lastly, a fifth emissions reduction case assumes both low geologic CO_2 sequestration and bioenergy in conjunction with the inability to produce synthetic fuels ("NoSF").

Scenario	Geologic CO_2 Sequestration Constraint	Primary Bioenergy Constraint	Synthetic Fuel Availability	Emissions Trajectory
Reference ("Ref")	Not available	Unconstrained	Not available	Endogenous
HS_HB	High (23.9 Gt CO_2)	High (232 EJ)	Available	Net-zero energy & industrial CO_2 emissions achieved in 2075
HS_LB	High (23.9 Gt CO_2)	Low (106 EJ)		
LS_HB	Low (9.6 Gt CO_2)	High (232 EJ)		
LS_LB	Low (9.6 Gt CO_2)	Low (106 EJ)		
LS_LB_NoSF	Low (9.6 Gt CO_2)	Low (106 EJ)	Not available	

Table 1. GCAM scenarios considered in this study. The 2100 values for the geologic CO_2 sequestration and modern primary bioenergy constraints are provided in parentheses. Carbon capture for utilization or storage is not available in the Reference scenario.

4.3. Decomposing emissions reductions

Global mitigation relative to the Reference scenario is decomposed for the five emissions reductions cases. The decomposition attributes mitigation to the following categories: electricity generation, hydrogen production, liquid fuels, gas, coal, cement, DAC, and 'BECCS – other'. Energy categories include emissions from production as well as use when applicable (e.g., for hydrocarbon fuels). Hydrocarbon categories do not include emissions associated with their use during the production of other sources of energy (e.g., electricity), as these emissions are attributed to that energy carrier. Cement only includes emissions from limestone calcination, as the emissions associated with process heat are attributed to the fuel used to produce this heat. 'BECCS – Other' includes net removals from BECCS in final energy applications within industry, whereas net removals from BECCS used in energy transformation sectors (electricity, hydrogen, liquid fuels) are attributed to those sectors. The sum of the disaggregated contributions in 2075 is within ±0.002 Gt CO_2 of the total energy and industrial emissions reported by the model.

For fossil hydrocarbon fuels, we further decompose emissions reductions relative to the Reference case using the product rule, noting that emissions equal production (less the amount used to produce other energy carriers) multiplied by the carbon intensity of the fuel (eq. 1). The carbon intensity (eq. 2) includes the carbon content of the hydrocarbon if it is combusted, less atmospheric carbon embodied in the fuel as well as emissions reductions from CCS, including carbon captured from bioenergy with CCS (BECCS) that results in negative emissions. By applying the product rule, the total change in emissions for a given fuel (eq. 3) can be disaggregated into a 'decarbonization effect' (eq. 4) and 'demand effect' (eq. 5). In equations 3-5, average refers to the mean of the Reference case and relevant emissions reduction scenario for the relevant metric.

(1) Emissions = production · carbon intensity

(2) Carbon intensity= $\frac{CO_2 \text{ emissions}}{\text{produced fuel}}$

(3) Δ emissions = (production average · Δ carbon intensity) + (Δ production · carbon intensity average)

(4) Decarbonization effect = production average · Δ carbon intensity

(5) Demand effect = Δ production · carbon intensity average

Additionally, we decompose emissions for liquids used in the transportation sector separately from their use in non-transportation applications. In these decompositions we also estimate the amount of 'out-of-sector CDR" required to bring total liquid emissions to net zero (or the emissions from liquid fuels in the Reference scenario less mitigation coming from the demand and decarbonization effects). A positive share for "out-of-sector CDR" implies that liquids emissions are net positive in the policy case and therefore that CDR would need to be purchased from other sectors to reach net-zero emissions. A negative share for "out-of-sector CDR" implies that liquid emissions are net negative in the policy case and that excess removals could be sold to other sectors (see panel C of Figure 2 and accompanying discussion).

Data Availability
The GCAM model and data system are available as an open-source package (https://github.com/JGCRI/gcam-core). The modified version of the model used in this study, as well as the scenario data, will be made publicly available upon publication of this study [doi to be included upon acceptance].

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References

[1] International Energy Agency (IEA). *World Energy Outlook 2025*. 2025. https://www.iea.org/reports/world-energy-outlook-2025.

[2] Shukla, Priyadarshi R., Jim Skea, Raphael Slade, et al., eds. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change (IPCC), 2022. https://doi.org/10.1017/9781009157926.

[3] McJeon, Haewon, Bryan K. Mignone, Patrick O'Rourke, et al. "Fossil Energy Deployment through Midcentury Consistent with 2°C Climate Stabilization." *Energy and Climate Change* 2 (December 2021): 100034. https://doi.org/10.1016/j.egycc.2021.100034.

[4] International Energy Agency (IEA). *Net Zero by 2050*. International Energy Agency (IEA), 2021. https://www.iea.org/reports/net-zero-by-2050.

[5] Intergovernmental Panel on Climate Change (IPCC), ed. "Mitigation Pathways Compatible with Long-Term Goals." In *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2023. https://doi.org/10.1017/9781009157926.005.

[6] Byers, Edward, Volker Krey, Elmar Kriegler, et al. "AR6 Scenarios Database (v1.1)." Intergovernmental Panel on Climate Change, November 9, 2022. https://doi.org/10.5281/zenodo.7197970.

[7] Browning, Morgan, James McFarland, John Bistline, et al. "Net-Zero CO2 by 2050 Scenarios for the United States in the Energy Modeling Forum 37 Study." *Energy and Climate Change* 4 (December 2023): 100104. https://doi.org/10.1016/j.egycc.2023.100104.

[8] Oliveira Laurin, Maria de, Rasmus Parsmo, Oskar Johansson, et al. "Is There a Role for Liquid Fuels in Future Low-Carbon Energy Systems? – A Continuous Interaction between Global Energy Systems Modeling and Local Energy Port Cluster Participation." *Applied Energy* 412 (June 2026): 127640. https://doi.org/10.1016/j.apenergy.2026.127640.

[9] Lehtveer, Mariliis, Selma Brynolf, and Maria Grahn. "What Future for Electrofuels in Transport? Analysis of Cost Competitiveness in Global Climate Mitigation." *Environmental Science & Technology* 53, no. 3 (2019): 1690–97. https://doi.org/10.1021/acs.est.8b05243.

[10] Oshiro, Ken, and Shinichiro Fujimori. "Role of Hydrogen-Based Energy Carriers as an Alternative Option to Reduce Residual Emissions Associated with Mid-Century Decarbonization Goals." *Applied Energy* 313 (May 2022): 118803. https://doi.org/10.1016/j.apenergy.2022.118803.

[11] Mignone, Bryan K., Leon Clarke, James A. Edmonds, et al. "Drivers and Implications of Alternative Routes to Fuels Decarbonization in Net-Zero Energy Systems." *Nature Communications* 15, no. 1 (2024): 3938. https://doi.org/10.1038/s41467-024-47059-0.

[12] Law, Jun Wen, Bryan K. Mignone, and Dharik S. Mallapragada. "Decarbonization Pathways for Liquid Fuels: A Multi-Sector Energy System Perspective." *Sustainable Energy & Fuels*, ahead of print, April 24, 2026. https://doi.org/10.1039/D5SE01654A.

[13] Daioglou, Vassilis, Andre P. C. Faaij, Deger Saygin, Martin K. Patel, Birka Wicke, and Detlef P. van Vuuren. "Energy Demand and Emissions of the Non-Energy Sector." *Energy & Environmental Science* 7, no. 2 (2014): 482–98. https://doi.org/10.1039/c3ee42667j.

[14] Speizer, Simone, Jay Fuhrman, Laura Aldrete Lopez, et al. "Integrated Assessment Modeling of a Zero-Emissions Global Transportation Sector." *Nature Communications* 15, no. 1 (2024): 4439. https://doi.org/10.1038/s41467-024-48424-9.

[15] Tu, Meiting, Ye Li, Lei Bao, et al. "Logarithmic Mean Divisia Index Decomposition of CO2 Emissions from Urban Passenger Transport: An Empirical Study of Global Cities from 1960–2001." *Sustainability* 11, no. 16 (2019): 4310. https://doi.org/10.3390/su11164310.

[16] Muratori, Matteo, Steven J. Smith, Page Kyle, Robert Link, Bryan K. Mignone, and Haroon S. Kheshgi. "Role of the Freight Sector in Future Climate Change Mitigation Scenarios." *Environmental Science & Technology* 51, no. 6 (2017): 3526–33. https://doi.org/10.1021/acs.est.6b04515.

[17] Fritzeen, Wade E., Patrick R. O'Rourke, Jay G. Fuhrman, et al. "Integrated Assessment of the Leading Paths to Mitigate CO2 Emissions from the Organic Chemical and Plastics Industry." *Environmental Science & Technology* 57, no. 49 (2023): 20571–82. https://doi.org/10.1021/acs.est.3c05202.

[18] Horowitz, Russell, Matthew Binsted, Morgan Browning, et al. "The Energy System Transformation Needed to Achieve the US Long-Term Strategy." *Joule* 6, no. 7 (2022): 1357–62. https://doi.org/10.1016/j.joule.2022.06.004.

[19] Hoehne, Christopher, Matteo Muratori, John Bistline, et al. "Transportation in Net-Zero Emissions Futures: Insights from the EMF-37 Model Intercomparison Study." *Energy and Climate Change* 6 (December 2025): 100211. https://doi.org/10.1016/j.egycc.2025.100211.

[20] Joint Global Change Research Institute. *Global Change Analysis Model (GCAM)*. R and C++. January 29, 2016, released n.d. https://github.com/JGCRI/gcam-core.

[21] Steinberg, Daniel C., Daniel P. Cherney, Bryan K. Mignone, Matthew Mowers, and Brian Sergi. "Decomposing Sources of Value for Electricity and Negative Emissions Technologies in Net-Zero Power Systems." *iScience* 29, no. 3 (2026). https://doi.org/10.1016/j.isci.2025.114187.

[22] International Energy Agency (IEA). "World Energy Balances 2023." 2023. https://www.iea.org/data-and-statistics/data-product/world-energy-balances.

[23] Bond-Lamberty, Ben, Pralit Patel, Joshua Lurz, et al. *JGCRI/GCAM-Core: GCAM 8.2*. June 3, 2025. https://doi.org/10.5281/zenodo.15581174.

[24] Patel, Pralit. *Core Model Proposal #404: Base Year Update: Move Model Base Year to 2021*. GCAM Model Documentation PNNL-37833. Joint Global Change Research Institute (JGCRI), 2025. https://jgcri.github.io/gcam-doc/cmp/404-Base_Year_Update_Move_Model_Base_Year_to_2021.pdf.

[25] Fricko, Oliver, Petr Havlik, Joeri Rogelj, et al. "The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century." *Global Environmental Change* 42 (January 2017): 251–67. https://doi.org/10.1016/j.gloenvcha.2016.06.004.

[26] Clarke, John F., and J. A. Edmonds. "Modelling Energy Technologies in a Competitive Market." *Energy Economics* 15, no. 2 (1993): 123–29. https://doi.org/10.1016/0140-9883(93)90031-L.

[27] Creutzig, Felix, N. H. Ravindranath, Göran Berndes, et al. "Bioenergy and Climate Change Mitigation: An Assessment." *GCB Bioenergy* 7, no. 5 (2015): 916–44. https://doi.org/10.1111/gcbb.12205.

[28] Fuhrman, Jay, Candelaria Bergero, Maridee Weber, et al. "Diverse Carbon Dioxide Removal Approaches Could Reduce Impacts on the Energy–Water–Land System." *Nature Climate Change* 13, no. 4 (2023): 341–50. https://doi.org/10.1038/s41558-023-01604-9.

[29] Fuhrman, Jay, Simone Speizer, Patrick O'Rourke, et al. "Ambitious Efforts on Residual Emissions Can Reduce CO2 Removal and Lower Peak Temperatures in a Net-Zero Future." *Environmental Research Letters* 19, no. 6 (2024): 064012. https://doi.org/10.1088/1748-9326/ad456d.

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