Energy and Climate Change 6 (2025) 100211

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

Transportation in net-zero emissions futures: Insights from the EMF-37 model intercomparison study

Christopher Hoehne [a], Matteo Muratori [a,i,*], John Bistline [b], Carol Lenox [c], David L. McCollum [d], Morgan Browning [c], Kara Podkaminer [e], Robert H. Beach [f], Robbie Orvis [g], Shiqi Ou [h], Page Kyle [j], Sharyn Lie [c], Megan Mahajan [g], Haewon McJeon [k], Catherine Ledna [a], Marc Melaina [e], Yongxia Cai [f], Christopher Ramig [c], Aniss Bahreinian [l], Nadejda Victor [m], Olivier Bahn [n], Kathleen Vaillancourt [o], Emma Starke [p], Allen Fawcett [c,j], James McFarland [c], Geoffrey Blanford [b], Trieu Mai [a], John Weyant [q]

[a] *National Renewable Energy Laboratory, Golden, CO, USA*
[b] *EPRI, Palo Alto, CA, USA*
[c] *US. Environmental Protection Agency, WA, D.C., USA*
[d] *University of Tennessee, Knoxville, TN, USA*
[e] *US. Department of Energy, WA, D.C., USA*
[f] *RTI International, Research Triangle Park, NC, USA*
[g] *Energy Innovation, San Francisco, CA, USA*
[h] *South China University of Technology, Guangzhou, Guangdong, China*
[i] *Pacific Northwest National Laboratory, Richland, WA, USA*
[j] *Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA*
[k] *KAIST Graduate School of Green Growth & Sustainability, Daejeon, South Korea*
[l] *California Energy Commission, Sacramento, CA, USA*
[m] *National Energy Technology Laboratory, Pittsburgh, PA, USA*
[n] *HEC Montréal, Montréal, QC, Canada*
[o] *ESMIA Consultants, Blainville, Canada*
[p] *School of Resource and Environmental Management, Simon Fraser University, Burnaby, BC, Canada*
[q] *Stanford University, Stanford CA, USA*

ARTICLE INFO

Keywords:
Transportation
Model comparison
Climate change
Deep decarbonization
Electrification
Energy systems

ABSTRACT

Transportation is currently the largest source of U.S. anthropogenic CO_2 emissions, at about a third of the total. Achieving net-zero emissions by mid-century will require substantial reductions in transportation emissions across passenger and freight travel. Here we leverage a model intercomparison study to explore the role of transportation in scenarios achieving net-zero economy-wide CO_2 emissions by 2050. We find the transport sector is poised to play the most significant role in reducing demand-side emissions, mostly driven by technology substitution, as modeling results suggest a limited role for mode shifting and for reduced use of personal car travel in the U.S. Among various technology solutions, models show agreement that passenger on-road vehicles will largely transition to electric vehicles (EVs), while solutions to decarbonize heavier travel modes are more diverse and include greater use of liquid biofuels and hydrogen. Research should continue to investigate the evolution of on-road electrification, the role of biofuels and hydrogen across heavier travel modes, and the role of mode shifting and travel behavior change to support personal transportation decarbonization at national and regional scales to temper the rapid growth in clean fuel and electricity demand.

* Corresponding author.
E-mail address: matteo.muratori@pnnl.gov (M. Muratori).

https://doi.org/10.1016/j.egycc.2025.100211

Available online 11 August 2025

1. Introduction

Transportation is the largest contributor to U.S. CO_2 emissions and will be a critical sector in addressing emission reductions. In 2022, U.S. economy-wide CO_2 emissions had declined relative to 2005 levels, but the transportation sector still accounted for 35 % of economy-wide emissions [1]. After a reduction during the COVID-19 pandemic, transportation emissions have returned to near pre-pandemic levels, and there is large uncertainty surrounding future emissions from transportation systems. While significant investments could accelerate the transition to a clean energy economy, the transportation sector is projected to continue to represent the largest share of energy-related emissions in the U.S [2]. In all scenarios, the 2023 Annual Energy Outlook (AEO) project economy-wide emissions decline of 28 % to 35 % by 2050 relative to 2005 and only a 9 to 10 % reduction in petroleum use by 2050 relative to 2022 [3].

The Stanford Energy Modeling Forum (EMF) continues the long-running practice of assembling working groups of modelers and subject matter experts in energy, economics, and the environment. The 37th EMF study (EMF-37) focuses on deep decarbonization and high electrification to explore transformations needed to achieve net-zero economy-wide emissions by 2050 [4]. Browning *et al.* provide an overview of EMF-37 and find broad agreement in deep decarbonization of the electricity sector alongside increased end-use electrification despite differences across 16 economy-wide models. All models rely on negative emissions technologies and land sinks to offset residual emissions and achieve net-zero emissions by mid-century. Residual CO_2 emissions remain primarily in the transportation and industrial sectors, to differing extents by model. This paper focuses on the U.S. transportation sector's role in economy-wide decarbonization by analyzing emissions and energy use evolution across a dozen models that provided sufficient transportation sector results.

Historically, transportation has been considered one of the hardest sectors to decarbonize, due to factors such as the complexity of moving people and goods reliably and conveniently, legacy infrastructure systems limiting options to travel (e.g., especially in the U.S. urban design that makes travel by car the only viable option for many), and lack of cost-effective alternatives to petroleum fuels, especially for non-road travel modes such as aviation and maritime [5–7]. At the same time, transportation sector emissions can be reduced through domestic policy and investment, while sectors such as industry are more susceptible to carbon leakage and competitiveness losses. While scenario studies have long shown that the U.S. and global transportation sector ultimately needs to significantly reduce emissions if the goal of net-zero emissions is to be achieved [8,9], a key question has always been how much transportation emissions can be reduced by 2050, given the various limitations mentioned above [10]. However, recent technology advancements, especially in batteries for electric vehicles [11], consumers' preferences, and global actions to achieve net-zero emissions by 2050 have spurred increased interest in understanding pathways to achieve 80–100 % emissions reduction across the entire transportation sector [12–14]. In this paper, we leverage modeling results from the EMF-37 study to address two key questions: 1) What is the role of the transportation sector in scenarios achieving net-zero economy-wide emissions by 2050? 2) What are the transportation emission mitigation strategies projected across different models that are used in the EMF-37 study and how are they realized (technologies, policies, behavioral changes or other system-level changes)?

2. Methods

2.1. Scenarios

On top of two core EMF-37 scenarios (*Reference* and *Net-Zero*), this paper includes five transportation study group (TSG) scenarios to explore the contribution of advanced technology, policy, and behavior assumptions in the transportation sector to the achievement of economy-wide net-zero CO_2 by 2050. We focus on the U.S. (vs North America) as the majority (10 of 12) of TSG reporting models only reported for the U.S. Table 1 provides an overview of the seven scenarios considered in this paper. Seven models filled out a detailed survey outlining the polices and assumptions used in transportation sector modeling for each of the scenarios. For a summary of these reported survey responses, see Supplementary Information section **S2**. For more details on modeling characteristics (e.g., spatial and technological detail, sectoral coverage and equilibrium approach, temporal foresight), see Table 2 and supplementary Table SM1 in Browning *et al.* [4]. The *Reference* scenario does not include Inflation Reduction Act incentives, though recent multi-model studies suggest that impacts of these tax credits on transport-sector outcomes are modest relative to other trends

Table 1
Scenario matrix for scenarios of interest in Transportation Study Group.

Scenario	Net-zero by 2050	Transport Behavior Change	Transport Advanced Technology	Transport Specific Policies
Reference				
Net-zero	✔			
TSG Behavior	✔	✔		
TSG Technology	✔		✔	
TSG Policy	✔			✔
TSG Tech & Policy	✔		✔	✔
TSG All Advanced	✔	✔	✔	✔

Table 2
Models that ran TSG scenarios. Note that all TSG scenarios include the net-zero target.

Model	Reference	Net-zero	TSG Behavior	TSG Technology	TSG Policy	TSG Tech & Policy	TSG All Advanced
ADAGE	✔	✔	✔		✔		✔
EPA-TIMES	✔	✔	✔	✔	✔	✔	✔
EPS	✔	✔					✔
FARM	✔	✔					✔
GCAM	✔	✔	✔	✔	✔	✔	✔
GCAM-USA	✔	✔					✔
gTech	✔	✔	✔	✔	✔	✔	✔
MA3T	✔		✔	✔	✔	✔	✔
MARKAL-NETL	✔	✔	✔	✔	✔	✔	✔
NATEM	✔	✔					✔
TEMPO	✔		✔	✔	✔	✔	✔
USREP-ReEDS	✔	✔					✔

Table 3
Availability of transportation emission reduction strategies not related to technology replacement across models. Two models (FARM and MA3T) did not report details on mitigation features.

Mitigation Category	ADAGE	EPA-TIMES	EPS	GCAM & GCAM-USA	gTech	MARKAL-NETL	NATEM	TEMPO	USREP-ReEDS
Endogenous changes to travel behavior and demand (e.g. telework)	Yes	Yes	No	Some	Yes	No	Some	Some	Yes
Endogenous mode shifting (e.g., from driving to transit)	Yes	No	No	Yes	Yes	No	No	Yes	No
New mobility solutions (micromobility, ride-haling, electric bikes)	No	No	No	No	No	No	No	Some	No
Transportation-specific policies (e.g., ZEV mandate)	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Ability to shift to different technologies/fuels (see details in Table 4)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 4
Availability of alternative fuel technologies by transportation subsector across models. *B* = Biofuel; *E* = electricity; H2 = hydrogen. The MA3T model does not capture rail, maritime or air subsectors. Models that did not fill out the survey are excluded. The FARM model is excluded from the table due to a lack of subsector detail reported; at the transport sector level, FARM reported fossil, electricity, and biofuel use but no hydrogen use.

Subsector	ADAGE	EPA-TIMES	EPS	GCAM	gTech	MA3T	MARKAL-NETL	NATEM	TEMPO	USREP-ReEDS
Light-duty	B, E, H_2	B, E, H_2	B, E, H_2	B, E, H_2	B, E, H_2	B, E	B, E, H_2	B, E, H_2	B, E, H_2	E
Commercial	B, E, H_2	B, E	B, E, H_2	B, E, H_2	B, E, H_2	B	B, E, H_2	B, E, H_2	B, E, H_2	E
Medium-duty	B, E, H_2	B, E, H_2	B, E, H_2	B, E, H_2	B, E, H_2	B	B, E, H_2	B, E, H_2	B, E, H_2	E
Heavy-duty	B, E, H_2	B, E, H_2	B, E, H_2	B, E, H_2	B, E, H_2	B	B, E, H_2	B, E, H_2	B, E, H_2	E
Passenger Rail		E	B, H_2	B, E, H_2	B, E		B, E	B, E, H_2	B, E	
Freight Rail		E, H_2	B, E, H_2	B, E, H_2	B, H_2		B	B, H_2	B	
Freight Maritime		B, E, H_2	B, E, H_2	B, E, H_2	B, H_2		B	B, H_2	B	
Air		B, E, H_2	B, E, H_2,	B, E, H_2	B			B	B	

and policies [15,2]. More information about the scenario specification for the reference and net-zero scenarios can be found in the EMF-37 overview paper [4].

2.1.1. Reference scenario

The *Reference* scenario uses each model's default set of assumptions on policy, behavior and technology. For transportation, cost reductions and performance improvements of various technologies are in line with historical trends or expected progress and there are incremental improvements in technology availability and charging and refueling infrastructure technologies. In this scenario, models assume no major behavioral changes (e.g., ownership and use of vehicles or modality).

All models ran the *Reference* scenario. Each model included the CAFE standards [16] in this and all subsequent scenarios. The gTech model included existing zero emission vehicle (ZEV) mandate policies in California and existing Low Carbon Fuel Standard (LCFS) regulations in Oregon and California. In this scenario, transportation sector emissions are projected to decrease between 2020 and 2050 by 1 to 40 %, with a median of 30 %.

2.1.2. Net-Zero scenario

The *Net-zero* scenario explores the least-cost pathways to achieve economy-wide net-zero CO_2 emissions by 2050. The target includes the following CO_2 source categories: fossil fuel combustion, non-energy use of fossil fuels, and industrial process emissions, carbon dioxide removal (CDR) technologies including direct air capture (DAC), bioenergy with carbon capture and storage (BECCS), and natural carbon management options such as land use, land-use change and forestry (LULUCF). For models that do not endogenously estimate LULUCF, there is an assumed constant sink of 800 Mt CO_2 per year [4]. This scenario uses each model's default assumptions for technology costs, complementary policies, and consumer preferences and is thus a baseline scenario for other net-zero scenarios, with two exceptions: MARKAL-NETL added electric powered vehicles to the commercial and heavy-duty truck subsectors; EPS added improvements to fuel economy standards, a minimum required EV sales and LCFS percentage, and reductions to travel demands or shifts to more efficient modes.

2.1.3. Net-zero TSG advanced technology

TSG Advanced Technology is a net-zero scenario designed to assess the potential impacts of accelerated transportation technology advancement in meeting CO_2 reduction targets. Seven models ran this scenario, implementing technology improvements that included rapid cost reductions, technology efficiency improvements, and improvements to EV charging and clean fuel infrastructure. The different models represented advanced technologies in a variety of ways given their unique model structures and resolutions, which means that the specific assumptions in this sensitivity are not harmonized (but still allow estimation of the impact of more aggressive technology improvement). Most, but not all, lowered investment costs for EVs and hydrogen technologies, though not to the same degree. Several models also decreased the costs of bioenergy and compressed natural gas technologies. In effect, the *TSG Advanced Technology* scenario represents a range of what leading modeling groups view as plausible future technology advancements.

2.1.4. Net-zero TSG advanced policy

TSG Advanced Policy is a net-zero scenario meant to explore the impact of transportation-specific policies in supporting sector-wide net-zero targets. Six of the models that ran the *TSG Advanced Technology* scenario also ran this scenario, plus one additional model. There was no consistent strategy used to implement the transportation policy landscape and its possible evolution. Several models implemented policies that no longer allowed the purchase of new gasoline or hybrid light-duty, heavy-duty, or commercial trucks starting in 2035. ZEV mandates were either added or improved in several models. Several other models improved upon already existing fuel economy standards or low carbon fuel standard policies. One model (gTech) also considered purchase incentives for EVs. Another model (TEMPO) implemented mandates requiring minimum amounts of biofuel in diesel, gas, and jet blends.

2.1.5. Net-zero TSG technology & policy

TSG Advanced Technology & Policy is a net-zero scenario combining the strategies implemented by each model that ran both the *TSG Advanced Technology* and *Advanced Policy* scenarios. All models implemented this scenario by combining the same strategies utilized in the

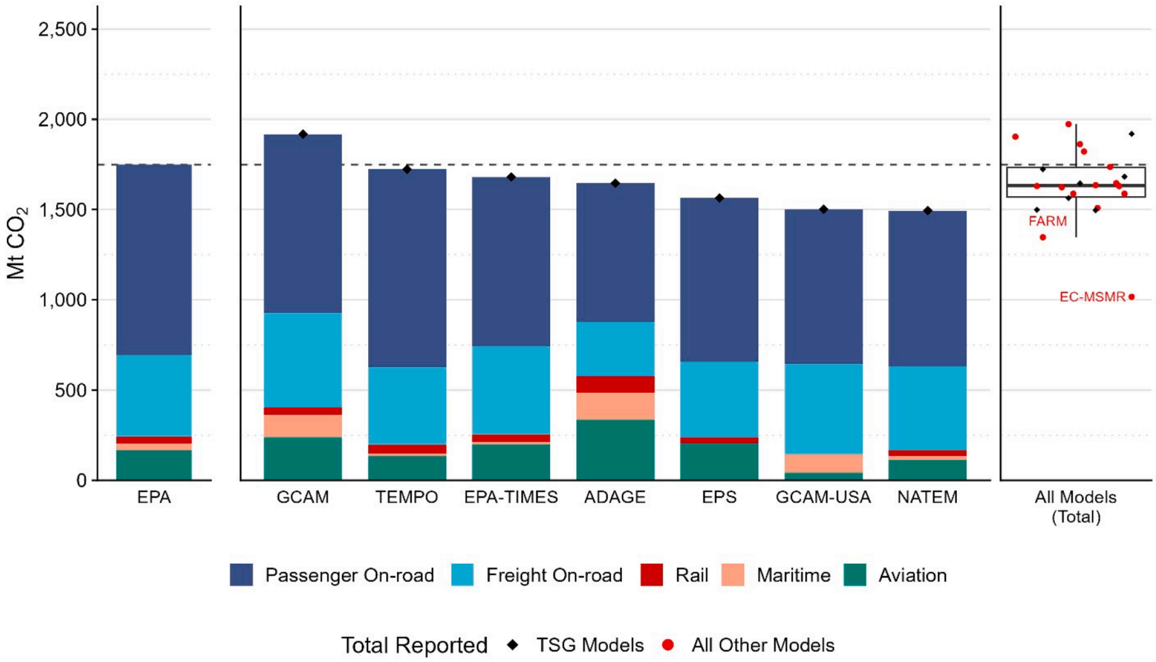

Fig. 1. 2019 transportation-related CO_2 emissions by subsector as reported by EPA (left bar) vs emissions estimated by seven TSG models. Total transportation emissions from all models (including those that didn't report sub-sector breakdown) are reported in the boxplot on the right. "Offroad" and "Other" subsectors excluded ("Other" includes pipelines, military, and lubricants).

TSG Advanced Technology and *Advanced Policy* scenarios. Half of reporting TSG models ran this scenario.

2.1.6. Net-zero TSG behavior

TSG Behavior is a net-zero scenario aimed at capturing the role of behavioral changes or choices in transport that help in meeting system-wide CO_2 reduction targets. The same seven models that ran the *TSG Advanced Policy* scenario also ran this scenario. Most of the models exogenously decreased light-duty travel demand, though the methods and amounts varied across models. These included a reduction in the amount of driving (i.e., less annual vehicle miles traveled), increases in public transportation use, and increased vehicle occupancy. One model (TEMPO) increased turnover of light-duty vehicles to bring in more efficient vehicles faster. Freight demand was also decreased in TEMPO via an increase in freight vehicle loads (average tonnage per vehicle).

2.1.7. Net-zero TSG all advanced scenario

TSG All Advanced is the most advanced net-zero transportation strategy, combining technology, policy, and behavior improvements throughout the transportation sector. All twelve models ran this scenario. Each of these models implemented the same strategies they utilized in their other TSG runs, but combined all the strategies used within their models for the *Advanced Technology, Advanced Policy*, and *Behavior* scenarios for the purposes of defining the *All Advanced* scenario.

Twelve models ran at least one of the TSG scenarios, with six models running all five (Table 2). We refer to the twelve models that ran at least one TSG specific scenario as TSG models. Ten TSG models cover all sectors of the energy system. One model, TEMPO, is a transportation sector only model. Another model, MA3T, only modeled passenger on-road travel. As a result, TEMPO and MA3T did not report the *Net-zero* scenario.

2.2. Modeling methodologies and assumptions

The models leveraged in this study have diverse characteristics in formulation (e.g., intertemporal optimization, general equilibrium, dynamic recursive, and systems dynamics), foresight (perfect vs. myopic), choice representation (logit vs. least cost), and sectoral coverage (economy-wide vs. transportation sector). These models also vary their parameterizations and their assumptions about how past decisions impact future choices and what alternatives exist to mitigate emissions. Leveraging these diverse approaches to simulate a set of consistent scenarios is at the core of EMF enabling a unique and comprehensive setting to identify robust insights around a topic of interest. Browning et al. [4] provides an overview of the key characteristics of the models included in the EMF-37 study.

Focusing on the transportation aspects of the models considered in this paper, Table 3 summarizes the fundamental climate change mitigation options for transportation systems (i.e., what mechanisms exist in the models to reduce transportation-related emissions) and Table 4 shows the technology choices available for various transportation subsectors for nine reporting models. Most models allow endogenous travel demand change such as reduced travel in response to higher travel prices and mode shifting (e.g., shifting from driving to rail). Most models include electric vehicle, hydrogen, and liquid biofuel alternatives for most travel modes. End-use service demands in all sectors can be adjusted in six of the models to address model constraints such as CO_2 reduction. The remaining models can only reduce demands exogenously.

Models also sometimes differ in their scope and what is included in the transportation sector. Fig. 1 shows 2020 modeled transport emissions by subsector against the 2019 EPA reported emissions [1]. 2020 is used as a baseline historical year (models report results in 5-year increments) and it is compared to 2019 reported emissions from EPA. 2020 modeling results do not capture impacts from the COVID-19 pandemic. Historical emissions appear quite different across models due to differing modeling assumptions and approaches. For example, GCAM includes international aviation and shipping in their reporting, leading to a greater base-year energy demand compared to domestic statistics from EPA and most other models. Other models like NATEM and EPS report significantly lower historical emissions due to segments within the transportation sector not included in the models. Five TSG models in Fig. 1 did not report emissions by transport subsector and instead only reported total sector emissions (shown in right boxplot).

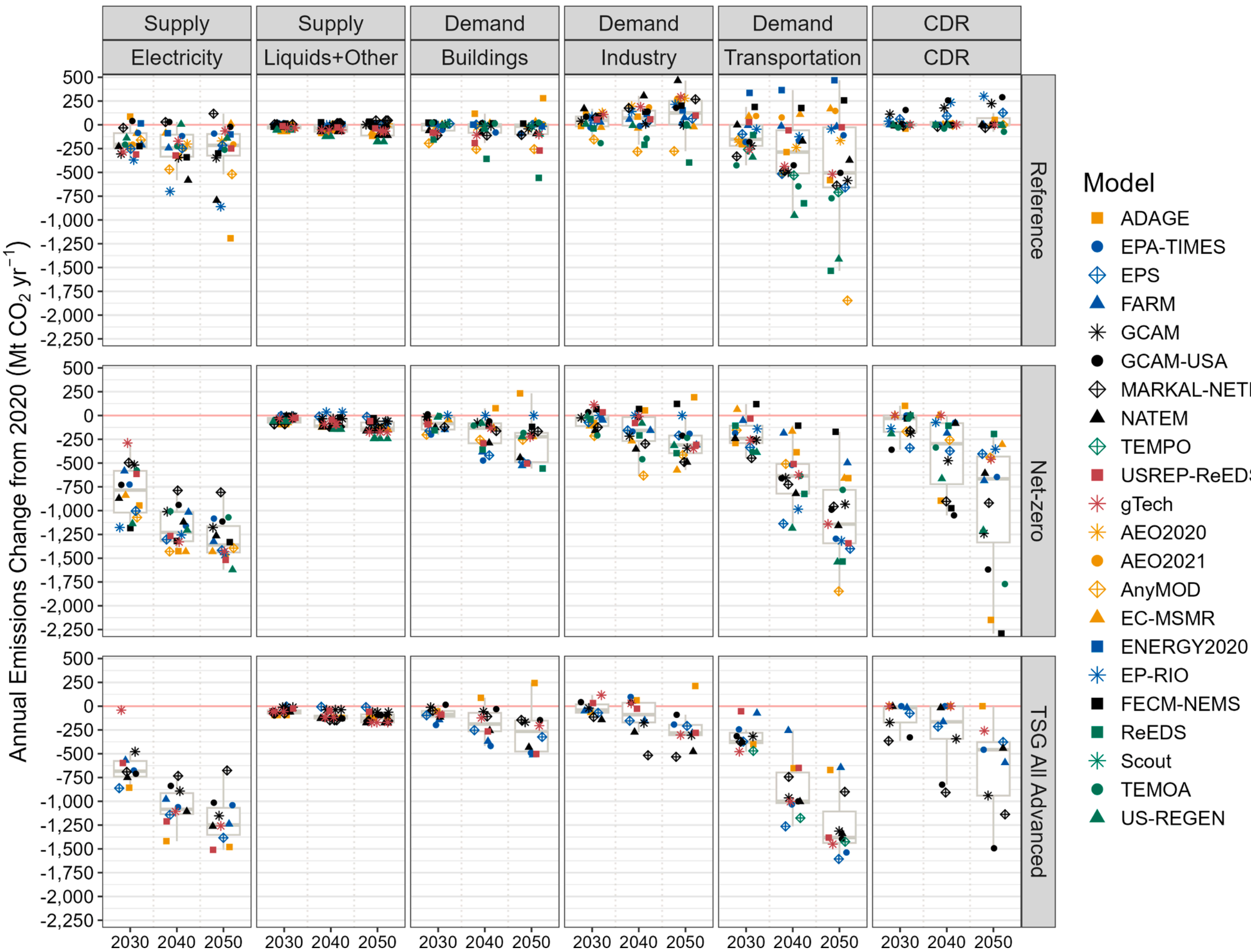

Fig. 2. Annual economy-wide U.S. carbon dioxide emission reductions from 2020 by sector, decade, across three scenarios. Reductions are presented for future years relative to each model's reported emissions in 2020 for inter-model consistency. CDR = Carbon Dioxide Removal (including LULUCF, bioenergy with CCS, and direct air capture). For annual economy-wide U.S. carbon dioxide emission reductions by sector for other TSG scenarios, see Figure S1.

3. Results: role of transportation in economy-wide decarbonization

The evolution of emissions from the transportation sector varies significantly across scenarios and models. Fig. 2 illustrates the extent of sectoral emission reductions by 2050 relative to 2020 levels across the *Reference, Net-zero*, and *TSG All Advanced* scenarios for all EMF-37 reporting models. For many models, transportation offers the largest CO_2 reductions in the *Reference* scenario from significant EV adoption and fuel economy improvements driven by existing technology competitiveness. The electricity sector is the other major source of emission reductions in the *Reference* scenario. For more details in the evolution of the electricity sector in EMF-37, see Browning et al. [4], Becker et al. [17], and Gao et al. [18].

In the *Net-zero* scenario, emissions from all sectors further decline under economy-wide carbon constraints . Magnitudes of sectoral mitigation vary by model, but the large role of transportation decarbonization reflects both its lower-cost abatement compared to other sectors and its largest share of current emissions, trends which are supported by earlier literature [19]. Across all net-zero scenarios, CDR is an important pathway for several models to achieve significant economy-wide decarbonization.[1] See Binsted et al. [20] for a detailed discussion of carbon management results and sensitivities in EMF-37 scenarios. In the *Net-zero* scenario, transportation sector CO_2 emissions were reduced between 2020 and 2050 by 22 % to 87 %, with a median of 44 %. Transport sector emissions are 27–97 % lower than 2005 levels in 2050 across models in the *Net-zero* scenario. In contrast, the electricity sector reductions in the *Net-zero* scenario span 75–102 % across models relative to 2005, while reductions in industry and buildings sectors are 68–100 % and 34–100 %, respectively. The fact that no model projects complete decarbonization of transportation (100 %), which is achieved by some models in other sectors, is driven by the lack of technologies to fully decarbonize all travel subsectors (e.g., aviation), higher marginal abatement costs of these subsectors, and lags associated with vehicle stock turnover. Still, the transportation sector is often the largest source of emission reductions in absolute terms (similar or greater than electricity supply and CDR). Differing modeling approaches and assumptions result in contrasting pathways to emission reductions across sectors, and the results show high uncertainty for future transportation emissions under all scenarios.

The *TSG All Advanced* scenario shows lower transportation emissions with 53–100 % reductions in transport sector emissions from 2005 to 2050 (compared to 27–97 % in the *Net-zero* scenario). In this scenario, transportation is the largest source of emission reductions by 2050, but this is achieved at a slower pace than the electricity sector (both reach similar magnitudes of reductions by 2050 but stock turnover effects limit near-term reductions in transportation). Despite high mitigation potential in transport, only one instance of full decarbonization is

[1] Note that there is an assumed constant sink of 800 Mt CO_2 yr^{-1} for models that do not endogenously estimate LULUCF.

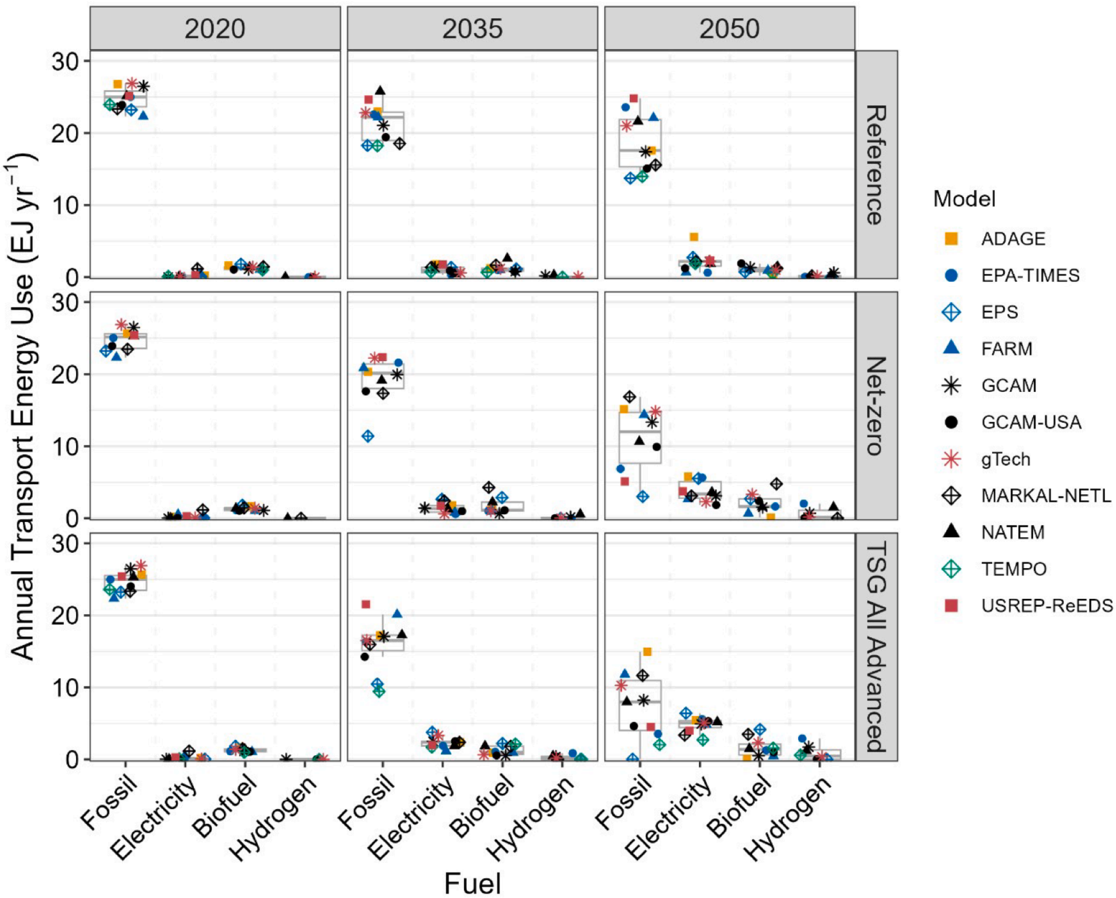

Fig. 3. Annual transport sector final energy use by fuel for three scenarios for TSG models. Note that the MA3T is excluded due to only reporting on-road energy use. For annual transport energy use for other TSG scenarios, see Figure S4. For on-road energy use only (with MA3T), see Figure S5.

reported by the EPS model. In total, 10 cases reached ≥80 % sector emission reductions: EPA-TIMES under four of five TSG scenarios (all except the *Behavior* scenario); GCAM-USA, gTech, USREP-ReEDS, and EPS only under *All Advanced*; and TEMPO under *All Advanced* and *Tech & Policy*. For more details on the levels of emissions mitigation achieved across TSG models and scenarios, see **Figures S1–3.**

Despite similarities in general trends, there are substantial cross-model differences in the extent of transportation emission reductions. This variation is significant in the *Reference* scenario, which indicates that models disagree on the evolution of transportation systems under their default set of assumptions (e.g., different degree of EV adoption without net-zero policies or advanced technology assumptions). The range of transport emission reductions remains large in *Net-zero* but narrows for the *All Advanced* scenario, indicating that transport-specific actions (related to travel behavior, transportation policies, and evolution of technology) consistently lead to greater reductions in transportation emissions across models. The following sections unpack and explain the differences across models in transportation emissions reduction across EMF-37 scenarios.

3.1. Transport energy use by fuel

Reductions in transportation emissions are largely driven by technology replacement, as a result of a transition from fossil fuels (which account for over 90 % of transportation energy use today) to mixes of electricity, biofuels, and hydrogen. However, there is a large variability in final energy use by fuel for various transportation modes across models and scenarios. Fig. 3 summarizes annual transport energy use by fuel across scenarios and Fig. 4 shows the breakdown of energy use by fuels across travel models for the *Net-zero* scenario.[2]

Petroleum accounts for most of the current transport consumption (90–99 % across models in 2020, or 22 to 27 EJ) but its role tends to decline over time in the *Reference* scenario down to 75–93 % (14 to 25 EJ) across models in 2050. While models agree on near-term fossil fuel consumption (Fig. 3 columns 1–2), there is high variation across models in 2050 across all scenarios (Fig. 3 column 3). For example, some models like TEMPO and EPS project major reductions in petroleum use by 2050 on the order of 40 % in the *Reference* scenario, while other models like USREP and EPA-TIMES project substantially flat petroleum demand.

Electrification is consistently projected to grow significantly over time but the degree of electrification varies greatly across models. In the *Reference* scenario, electricity demand from the transportation sector grows to between 0.62 and 5.6 EJ (170 to 1600 TWh) by 2050. In the *Net-zero* scenario, electricity use ranges between 1.9 to 6.4 EJ (530 to 1800 TWh) in 2050. Petroleum use ranges from 0.03 EJ to 17 EJ by 2050 in *Net-zero*, a 0–72 % reduction from 2020 levels. In *TSG All Advanced*, the transition away from petroleum is slightly higher (ranging from 0.03 to 15 EJ in 2050) but not fundamentally different. In the *All Advanced* scenario, four out of twelve models (EPA-TIME, EPS, GCAM-USA, and TEMPO) report 2050 transport electricity use higher than fossil fuel use, indicating a major shift towards vehicle electrification.

Similarly, there is variation across models in the extent of future

[2] Note that we do not report the energy use in units per service delivered due to limited model reporting. As a result, it is important to keep in mind that battery electric and fuel cell electric vehicles are commonly two to four times as efficient as internal combustion engine vehicles at delivering service (passenger kilometers traveled, tonne-miles traveled) per unit of energy.

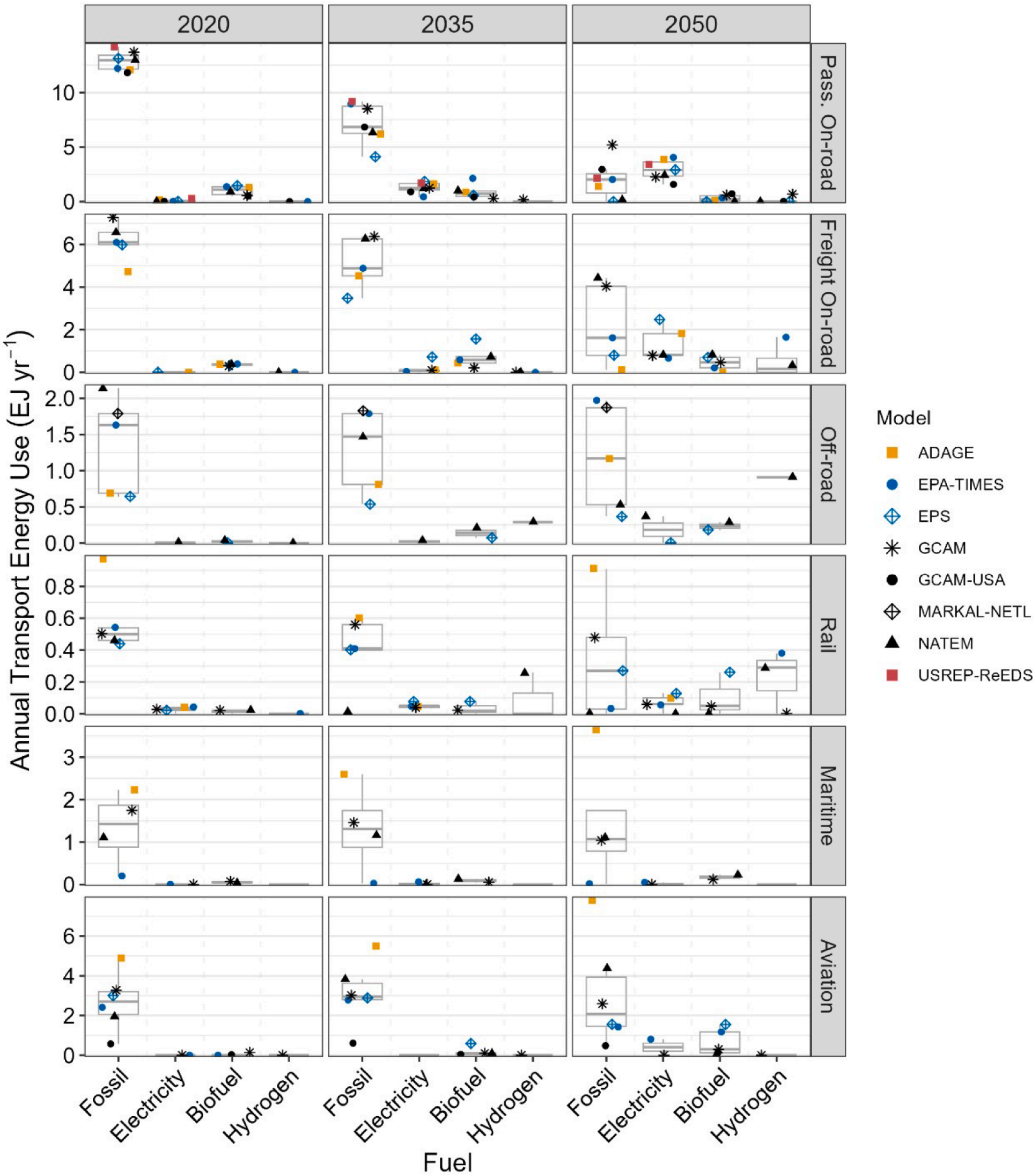

Fig. 4. Annual transport sector final energy use by year, fuel, and travel mode for the Net-zero scenario. For annual transport energy use for the TSG All Advanced scenario, see Figure S6.

biofuel and hydrogen demand: biofuel demand ranges between 0.1 to 4.8 EJ in 2050 (compared to 1.0 to 1.8 EJ in 2020), and hydrogen between 0 and 2.9 EJ (compared to virtually 0 in 2020) across TSG models. 2050 transportation biofuel use is higher than electricity in three models under the *Net-zero* Scenario (GCAM-USA, MARKAL-NETL, and gTech) and only for MARKAL-NETL in four of the five TSG net-zero scenarios. Higher biofuel usage in some scenarios is driven by its net negative emissions potential alongside its ability to be a drop-in equivalent to fossil fuels through use with existing capital and infrastructure. The ADAGE and EPS models reported they can consider hydrogen as an alternative in subsectors modes (Table 3), but both did not report any transport hydrogen use across scenarios.

Looking at fuel use across travel modes in the *Net-zero* scenario (Fig. 4), models show agreement that passenger on-road vehicles will largely transition to EVs with very small roles for biofuels or hydrogen. Electricity almost entirely replaces petroleum in the *All Advanced* scenario (**Figure S6**). Solutions to decarbonize heavier travel modes are more diverse and include greater use of hydrogen or biofuels, with different degrees of success across models. Fossil fuel use drops significantly for passenger and freight on-road (and for rail in some models) but much less for other modes. Models project that liquid fuels (fossil or biofuel) will be needed to power maritime vehicles with extremely limited use of electricity or hydrogen. Similarly, models project that liquid fuels will primarily power aviation with limited electrification or hydrogen potential. Hydrogen is projected to play a larger role in decarbonizing rail and offroad modes with some potential to support decarbonizing on-road freight and minimal to no support in maritime, aviation, and passenger on-road. For a discussion of EMF-37 hydrogen results across a broader set of scenarios and sectors, see Melaina *et al.* [21].

3.2. *Transport decarbonization pathways*

Pathways to reach decarbonization in transport vary widely due to differing modeling approaches and assumptions. Fig. 5 shows the evolution of CO_2 emissions by subsector for six TSG models under the *TSG All Advanced* scenario (see **Figure S2** for the *Net-zero* results). While models disagree on the decarbonization potential across transportation

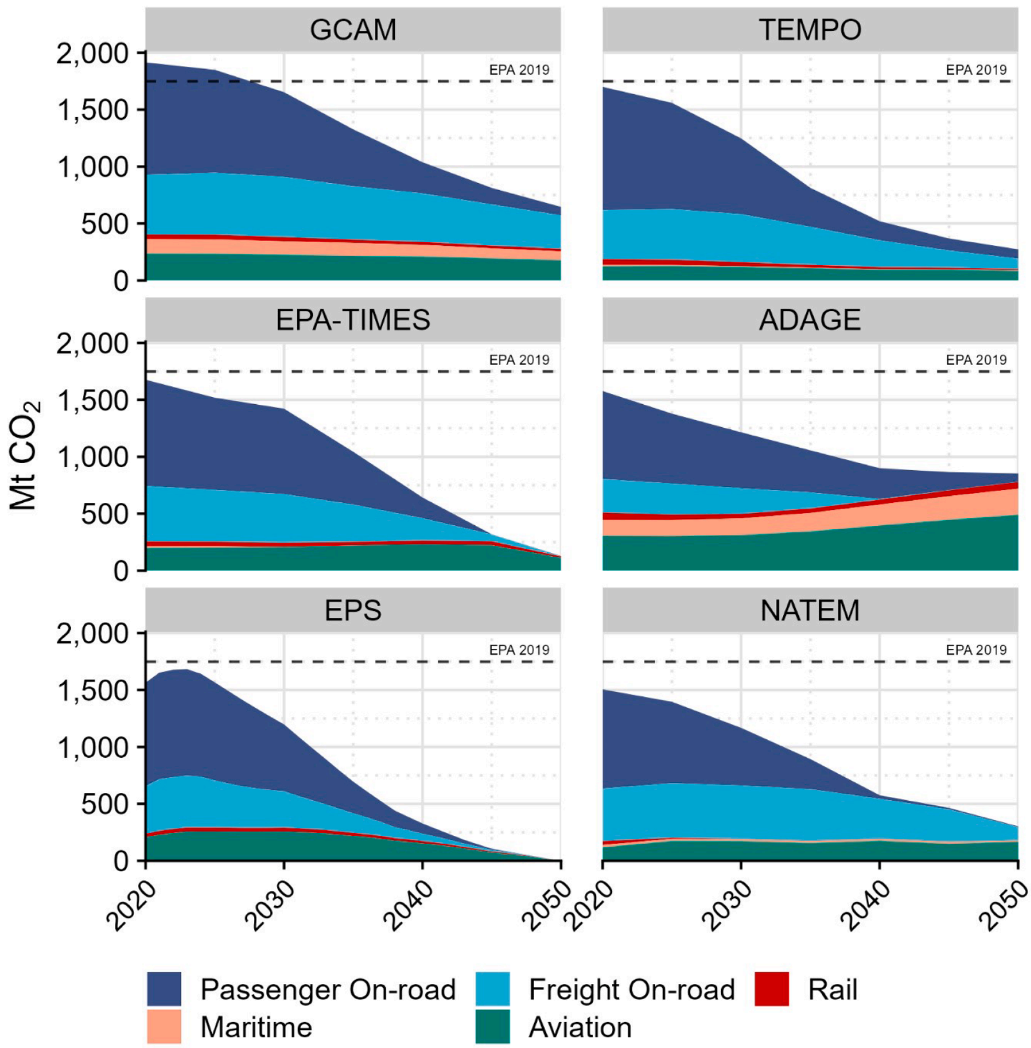

Fig. 5. Emissions by subsector for reporting TSG models in the TSG All Advanced scenario over time. “Offroad” and “Other” subsectors excluded. The GCAM-USA model was omitted here in favor of its more comprehensive counterpart, and all other TSG models not shown did not report emissions by subsector.

subsectors, on-road decarbonization is the most common. Across six models reporting emissions by subsector for the *TSG All Advanced* scenario, all agree that significant mitigation occurs in on-road travel, especially passenger on-road (i.e., personal light-duty vehicles); five of six models show 93–100 % mitigation of passenger on-road CO_2. Two models (EPA-TIMES and EPS) see near complete mitigation of on-road emissions by 2050 (< 5 Mt CO_2) across six scenarios. Three models project 100 % mitigation of freight on-road emissions across six TSG scenarios (ADAGE, EPS, and EPA-TIMES) with each scenario including at least policy levers. Overall, technology and policy levers play the stronger roles in driving on-road decarbonization, with policies being slightly more impactful in the freight sector.[3]

Despite wide agreement in decarbonization potential for on-road travel, 2050 fossil fuel use in transport remains highly varied across models under net-zero futures. For some models, this is due to more limited alternatives for decarbonizing non-road subsectors. Across net-zero scenarios in 2050, the ADAGE model sees the highest average fossil fuel use despite decarbonizing 91 % of on-road travel. This is driven by increasing aviation and maritime freight demand leading to consistent fossil fuel use of 15 ($\pm$0.21) EJ across all net-zero scenarios. MARKAL-NETL had limited reporting of emissions by mode but projects 9–17 EJ fossil fuel use in 2050. This high fossil fuel use is driven by fewer alternative fuel options than other models including no alternative fuel options for aviation, and only biofuel alternatives in freight rail and freight maritime (see Table 3 in section 2.3). We do not report technology stock or sales shares as only one model (TEMPO) reported these data.

Five TSG models and one non-TSG model reported breakdowns of passenger transportation service demand. Four TSG models report passenger service demand for all five modal categories (road, bike and walk, rail, aviation, and other). Fig. 6 shows the passenger transport service demand by mode over time for reporting models under the *Reference* scenario and the *TSG All Advanced* scenario. Note that differences in base-year demand are the result of differing assumptions and datasets used for calibration. Models agree that there is limited potential to shift away from on-road travel. All six models reporting passenger demand show similar and gradual increases in demand over time in the *Reference* scenario, and all but the TEMPO model sees total demand continue to

[3] EPA-TIMES on-road emissions reach near zero by 2050 under TSG scenarios with at least policy levers (*Policy, Tech & Policy*, and *All Advanced*) indicating strong impacts from policy levers for on-road decarbonization in the model. EPS only modeled one TSG scenario (*All Advanced)* but also sees near zero on-road emissions in the *Net Zero* reference scenario (1 Mt CO_2 passenger and 56 Mt CO_2 freight in 2050). In the six scenarios reaching full decarbonization for freight on-road, all six had at least policy levers, four had technology levers, and none had only behavior levers (three *TSG All Advanced*, two *TSG Policy*, and one *TSG Technology & Policy*).

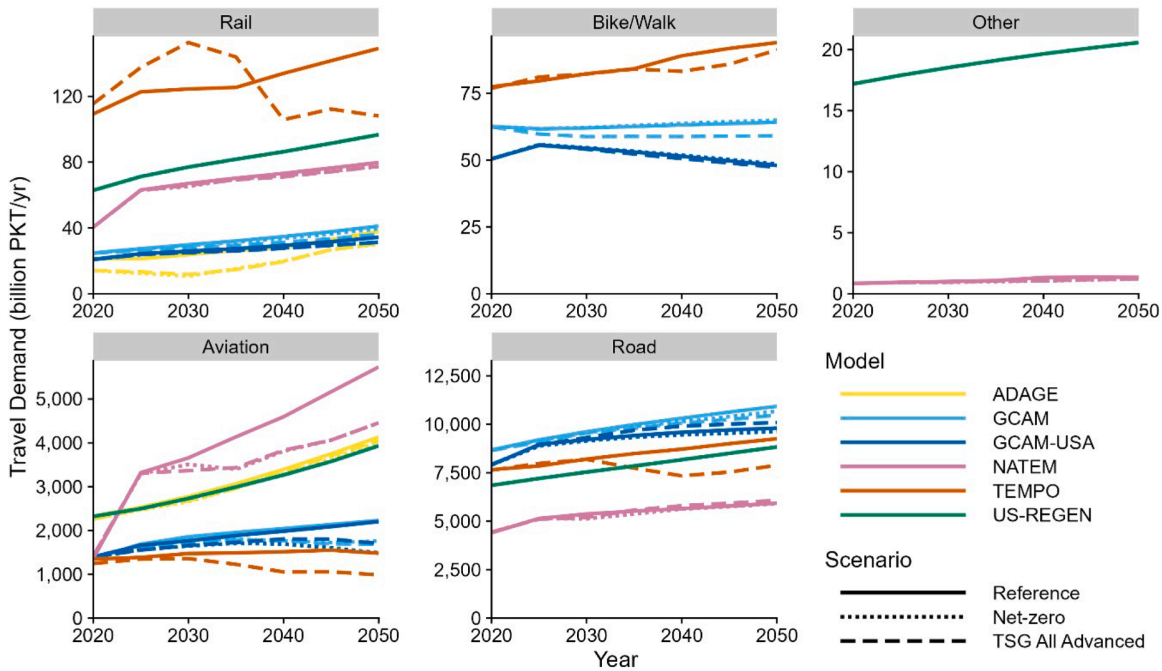

Fig. 6. Transport service demand by mode for five reporting TSG models. One non-TSG-reporting model reported transport service demand in the reference case and is included (US-REGEN).

grow at similar rates in the *TSG All Advanced* scenario. These trends in passenger service demand indicate that economy-wide models show limited potential for policy and behavior change to enable mode shifts and travel demand management, but this may be a consequence of models not fully capturing non-technology mitigation options in the transportation sector.

Future aviation demand has the most disagreement across models ranging from 68 % increased demand to 30 % reduced demand across all models' net-zero scenarios. Combined with more limited mitigation options, this can result in large increases in aviation emissions for some models under net-zero scenarios. ADAGE predicts increases in aviation emissions of 44 % in each of its four net-zero scenarios, and NATEM predicts increases in aviation emissions of 68 % across two net-zero scenarios.

4. Discussion

The results from 37th EMF study on economy-wide deep decarbonization and high electrification pathways demonstrate both robust insights into the transport sector's role in achieving net-zero emissions by 2050 as well as key remaining uncertainties that need to be addressed.

4.1. Robust insights

The transport sector offers the largest demand-side mitigation potential across net zero scenarios. In most models, transportation is also the largest source of end-use CO_2 emission reductions in reference scenarios given the competitiveness of electric vehicles and continued improvements in fuel economy of internal combustion engine vehicles even without net-zero policies. Under net-zero scenarios, transportation emissions are reduced even more in most models. EMF-37 results consistently show that the largest contribution to transportation emissions reduction is replacement of petroleum with electricity, and to a lesser extent biofuels and hydrogen. There is wide agreement that decarbonizing on-road vehicles by leveraging EV adoption will be easier than other abatement options, even though the degree and timing of electrification varies across models. Six models projected a 93–100 % mitigation of passenger on-road emissions by 2050. Models project that liquid fuels (fossil or biofuel) will be needed to power maritime vehicles with extremely limited use of electricity or hydrogen. Similarly, models project that liquid fuels will primarily power aviation with limited electrification or hydrogen potential. Hydrogen is projected to play a larger role in decarbonizing rail and offroad modes with some potential to support decarbonizing on-road freight, but little potential is seen for maritime, aviation, or passenger on-road (cf., [21]).

Transportation is projected to become a major driver of increased electricity demand, primarily due to passenger on-road electrification. However, the speed and extent of electricity demand growth depends on the success of EVs across applications, their efficiency, and the role of hydrogen, which could require about twice as much electricity if produced via electrolysis and other factors.. These uncertainties result in large discrepancies across models; transport electricity use ranges between 1.9 to 6.4 EJ (530 to 1800 TWh) across net-zero scenarios by 2050. This demand growth could be significant compared to today's electricity demand (about 4000 TWh), but other studies have shown that there could be even greater uncertainties than expected in transportation electricity demand considering EV adoption dynamics, technologies like autonomous vehicles, induced demand due to cheaper cost of travel, and increasing urban congestion [12,22–25]. To aid in limiting the potential rapid growth in clean electricity generation in support of transportation electrification and a resilient power grid, managing EV charging smartly [26] and managing the growth in vehicle travel will be important [12]. Future research should continue to carefully understand the rate of electrification across sectors and the options to support a more resilient electricity sector.

Nearly all models report residual emissions from transportation in even the most advanced net-zero scenarios. This necessitates a reliance on negative carbon technologies (i.e., LULUCF, BECCS, and DAC) to achieve net-zero, but it also highlights opportunities for further research to understand how to address decarbonization of hard-to-electrify transportation segments (e.g., aviation, maritime) and investigating the role of demand reduction and mode shifting in national decarbonization efforts. Our results further demonstrate why transportation is considered the most difficult sector to fully decarbonize as residual emissions from fossil fuels in even the most aggressive net-zero scenarios are common.

Results presented here indicate travel mode shifting may have a limited role as a mitigation strategy or that economy-wide models lack the needed representation to capture greater contributions from mode shifting (particularly due to a lack of alternatives to personal cars). Despite this, many studies argue managing travel demand and vehicle travel through mode shift or other measures will be required to decarbonize the sector [27,28,12,24,29,30]. The IPCC's Sixth Assessment Report [5] points to global emissions reduction potential from switching to public transport and bicycling to be similar in magnitude to the use of biofuels in transportation or more efficient shipping and aviation, but the EMF-37 results do not report such a big opportunity in the US. More research is needed, especially in national and global transportation and economy-wide modeling to understand the mechanisms and circumstances that could lead to measurable impacts towards mode shifting and limiting travel growth in support of sector decarbonization.

4.2. Key uncertainties

While some robust insights were revealed when comparing model results, there remain key uncertainties around pathways to transportation decarbonization. Models agree on the prevalent role of technology substitution to reduce transportation emissions, but the degree of petroleum replacement and the mix of clean technologies (i.e., EVs, hydrogen, and biofuels) used in the transportation subsectors vary across models. These differences depend on the technologies represented in each model, their assumptions related to current and future costs, and model reliance on negative emission technologies to achieve net-zero. The evolution of transport fossil fuel consumption under net-zero scenarios is highly varied to 2050 and there is great uncertainty for future transport energy use when combining strategies across technology, policy, and behavior. The narrowest (but still very large) range of fossil fuel demand across models in 2050 occurs under the *TSG Advanced Technology* scenario (4.4 to 13 EJ), and the widest range occurs under the *TSG All Advanced* scenario (0.03 to 15 EJ). In addition to transformations in the transport sector, high uncertainty of fossil fuel use is also driven by the cost and availability of compensating CDR facilities [31].

High uncertainty in future aviation travel demand with fewer and more constrained mitigation options highlights an area for further focus. Aviation is least open to full electrification because of the mass of the batteries, and while the energy content of hydrogen is almost three times that of kerosene, challenges arise regarding storage. These challenges of electrification and storing hydrogen point to sustainable aviation fuel as the main practical fuel solution for larger, longer-range aircraft which serves the majority of aviation energy demand. These challenges are also apparent in the modeling results which show aviation contributing to a much larger share of 25–50 % residual 2050 emissions compared to about 10 % today. Other research has indicated optimistic reductions in aviation demand and improvements in aircraft efficiency will not be enough for mitigation [32]. Partial uncertainty in this analysis may derive from differing modeling assumptions surrounding international travel; explicitly considering international aviation in addition to domestic demand may further expand the uncertainty of future emissions and mitigation needs.

Across the economy-wide model results analyzed here, mode shift and managing travel demand (e.g., through behavior change or incentivized polices like carpooling) are not reported as significant in these scenarios; only the GCAM and TEMPO models reported walk and bicycle travel demand, and all models lack representation of many alternative modes such as micromobility (e.g., electric bikes) or distinguish well between transit modes (intercity bus, local bus, metro rail, commuter rail, etc.). In general, economy-wide models have not been developed to capture enough dynamics around mobility needs and ways to satisfy them to uncover the extent to which mode shifting and reducing travel demand could be viable to support decarbonization. A lack in heterogenous travel supply options including novel and emergent mode representation may be a critical weakness calling for model enhancement or coupling with more detailed models. As the participating models and the 37th EMF is focused on North American economies, this lack of representation may be in-part influenced by highly car-dependent infrastructure in the U.S [33,34] and strong preferences for flexibility offered by personal vehicles [35]. While the U.S. may be slower to adopt alternatives to private cars as a result, other countries around the world may find more applicability for travel mode shift and managing travel demand to close the mitigation gap [5]. For example, in IEA's Net-zero by 2050 global study, up to 38 % of expected travel demand is avoided by 2050 due to smart city planning and densification [36], but this will require local zoning changes and lower barriers to building. Yet there is limited research that demonstrates modeling of specific policies and strategies at the national or global level to achieve this.

All five models reporting on-road travel service demand project steady increases. However, recent literature surrounding travel service demand indicates diverging futures are possible depending on different policies and investments in coming decades. As a result, various drivers of evolving travel demand may dictate differing needs for optimal design of future power systems such as incentives for flexible EV charging [37] or for greater expansions of total clean electricity supply than typically projected [12]. Addressing these uncertainties will be important to evaluate the potential impacts of different policies and guide optimal design and operation of the transitioning U.S. electric power system.

These key remaining uncertainties should be investigated further to understand opportunities to realize transport sector mitigation goals. Research that targets the nexus of these uncertainties may find unforeseen synergies or additional barriers to reaching mitigation. For example, widespread adoption of autonomous vehicles may induce significant on-road demand but in turn offer an alternate pathway to decarbonize aviation by offering a competitive long distance travel option [38,39]. As a result, this tradeoff could greatly increase the need for annual clean electricity supply needs beyond current projections. Alternatively, more robust findings at the national or global scale on potential to avoid travel demand growth and promoting mode shifting away from personal cars could lower transport electrification needs and ease the expansion of clean electricity supply.

5. Conclusions

Drawing on model results from the 37th Energy Modeling Forum, this paper evaluates the role of the transportation sector in achieving net-zero economy-wide decarbonization by 2050. We derive insights on future transportation decarbonization pathways by comparing a collection of emissions and energy use modelling results across a dozen models. We compare modelling results across *Reference* and *Net-zero* scenarios as well as five transportation-specific variations of net-zero scenarios that varied assumptions in transport technology advancement, transport-specific policy enablement, and travel behavior change. We characterize the impact of key uncertainties in transport decarbonization pathways to inform decision makers as well as document robust insights based on consistent trends across models.

We find the U.S. transport sector is poised to play the most significant role in reducing economy-wide carbon emissions in coming decades, and this is mostly driven by major fuel switching from petroleum to electricity, biofuels, and hydrogen. However, there remains large uncertainties of future transport energy use with models disagreeing on the amount of remaining fossil fuel use and the mix of different alternative fuels across subsectors. This uncertainty is exacerbated by high variation in future aviation trends (growth in demand and sustainable aviation fuel availability). Additionally, we find economy-wide models may lack the capabilities to capture mode shifting or travel demand management; this highlights a need for future national and economy-wide transportation sector modeling to understand the mechanisms that could lead to measurable impacts to further mitigate emissions and the help tame the rapid growth in decarbonized power supply. Future work should continue to investigate and address these remaining uncertainties, and decision makers should utilize these results to inform managing the risk and prioritization of future investments and polices to achieve ambitious goals of transportation sector decarbonization.

CRediT authorship contribution statement

Christopher Hoehne: Writing – review & editing, Visualization, Formal analysis, Writing – original draft, Methodology. **Matteo Muratori:** Writing – review & editing, Supervision, Writing – original draft, Conceptualization. **John Bistline:** Writing – review & editing. **Carol Lenox:** Writing – original draft, Data curation, Writing – review & editing, Methodology. **David L. McCollum:** Writing – original draft, Writing – review & editing. **Morgan Browning:** Writing – review & editing, Methodology, Conceptualization, Data curation. **Kara Podkaminer:** Writing – review & editing, Supervision, Funding acquisition. **Robert H. Beach:** Writing – review & editing, Visualization. **Robbie Orvis:** Writing – review & editing. **Shiqi Ou:** Writing – review & editing. **Page Kyle:** Writing – review & editing. **Sharyn Lie:** Writing – review & editing. **Megan Mahajan:** Writing – review & editing. **Haewon McJeon:** Writing – review & editing. **Catherine Ledna:** Writing – review & editing. **Marc Melaina:** Writing – review & editing. **Yongxia Cai:** Writing – review & editing. **Christopher Ramig:** Writing – review & editing. **Aniss Bahreinian:** Writing – review & editing. **Nadejda Victor:** Writing – review & editing. **Olivier Bahn:** Writing – review & editing. **Kathleen Vaillancourt:** Writing – review & editing. **Emma Starke:** Writing – review & editing. **Allen Fawcett:** Writing – review & editing, Supervision, Conceptualization. **James McFarland:** Supervision, Conceptualization, Writing – review & editing. **Geoffrey Blanford:** Writing – review & editing, Supervision, Conceptualization. **Trieu Mai:** Writing – review & editing, Supervision, Conceptualization. **John Weyant:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

James McFarland, Allen Fawcett, John Weyant, Trieu Mai, and Geoff Blanford are all editors for the special issue for which this manuscript is being submitted.

Acknowledgements

The views expressed in this paper are those of the individual authors and do not necessarily reflect those of their respective institutions including but not limited to Environmental Protection Agency, the Department of Energy (DOE), the U.S. Government, or EPRI. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes. This work was authored in part by the National Renewable Energy Laboratory for the DOE under Contract No. DE-AC36–08GO28308. This work was funded by the National Energy Technology Laboratory, in part, through a site support contract. Neither the United States Government nor any agency thereof, nor any of its employees, nor the support contractor, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

The authors would like to acknowledge the support of the EMF-37 modeling teams for data submission and contributions to modeling surveys that made this work possible.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2025.100211.

References

[1] EPA, (Environmental Protection Agency), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022, 2024. EPA 430R-24004.

[2] J. Bistline, G. Blanford, M. Brown, D. Burtraw, M. Domeshek, J. Farbes, A. Fawcett, A. Hamilton, J. Jenkins, R. Jones, B. King, H. Kolus, J. Larsen, A. Levin, M. Mahajan, C. Marcy, E. Mayfield, J. McFarland, H. McJeon, R. Orvis, N. Patankar, K. Rennert, C. Roney, N. Roy, G. Schivley, D. Steinberg, N. Victor, S. Wenzel, J. Weyant, R. Wiser, M. Yuan, A. Zhao, Emissions and energy impacts of the Inflation Reduction Act, Science (1979) 380 (2023) 1324–1327, https://doi.org/10.1126/science.adg3781.

[3] EIA, (Energy Information Administration), Issues in Focus: Inflation Reduction Act Cases in the AEO2023, 2024. https://www.eia.gov/outlooks/aeo/IIF_IRA/.

[4] M. Browning, J. McFarland, J. Bistline, G. Boyd, M. Muratori, M. Binsted, C. Harris, T. Mai, G. Blanford, J. Edmonds, A.A. Fawcett, O. Kaplan, J. Weyant, Net-zero CO2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study, Energy Clim. Change 4 (2023) 100104, https://doi.org/10.1016/j.egycc.2023.100104.

[5] IPCC, (Intergovernmental Panel on Climate Change), 2022. IPCC WGII Sixth Assessment Report 1–10.

[6] S. Kahn Ribeiro, M.J. Figueroa, F. Creutzig, C. Dubeux, J. Hupe, S. Kobayashi, Chapter 9 - Energy End-Use: transport. Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012, pp. 575–648.

[7] M. Muratori, S.J. Smith, P. Kyle, R. Link, B.K. Mignone, H.S. Kheshgi, Role of the freight sector in future climate change mitigation scenarios, Environ. Sci. Technol. 51 (2017) 3526–3533, https://doi.org/10.1021/acs.est.6b04515.

[8] L. Clarke, Y.-M. Wei, A. De La Vega Navarro, A. Garg, A.N. Hahmann, S. Khennas, I. M.L. Azevedo, A. Löschel, A.K. Singh, L. Steg, G. Strbac, K. Wada, Energy Systems, in: P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Eds.), Climate Change 2022 - Mitigation of Climate Change, Cambridge University Press, 2023, pp. 613–746, https://doi.org/10.1017/9781009157926.008.

[9] USGCRP, in: A.R. Crimmins, C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, T.K. Maycock (Eds.), Fifth National Climate Assessment, U.S. Global Change Research Program, Washington, DC, USA, 2023, https://doi.org/10.7930/NCA5.2023.

[10] F. Creutzig, P. Jochem, O.Y. Edelenbosch, L. Mattauch, D.P.van Vuuren, D. McCollum, J. Minx, Transport: a roadblock to climate change mitigation? Science (1979) 350 (2015) 911–912, https://doi.org/10.1126/science.aac8033.

[11] M. Muratori, M. Alexander, D. Arent, M. Bazilian, P. Cazzola, E.M. Dede, J. Farrell, C. Gearhart, D. Greene, A. Jenn, M. Keyser, T. Lipman, S. Narumanchi, A. Pesaran, R. Sioshansi, E. Suomalainen, G. Tal, K. Walkowicz, J. Ward, The rise of electric vehicles—2020 status and future expectations, Progr. Energy 3 (2021) 022002, https://doi.org/10.1088/2516-1083/abe0ad.

[12] C. Hoehne, M. Muratori, P. Jadun, B. Bush, A. Yip, C. Ledna, L. Vimmerstedt, K. Podkaminer, O. Ma, Exploring decarbonization pathways for USA passenger and freight mobility, Nat. Commun. 14 (2023) 6913, https://doi.org/10.1038/s41467-023-42483-0.

[13] P. Jaramillo, S. Kahn Ribeiro, P. Newman, S. Dhar, O.E. Diemuodeke, T. Kajino, D. S. Lee, S.B. Nugroho, X. Ou, A. Hammer Strømman, J. Whitehead, Transport, in: P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Eds.), Climate Change 2022 - Mitigation of Climate Change, Cambridge University Press, 2023, pp. 1049–1160, https://doi.org/10.1017/9781009157926.012.

[14] K. Riahi, R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, D.P. van Vuuren, Mitigation pathways compatible with long-term goals, in: P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Eds.), Climate Change 2022 - Mitigation of Climate Change, Cambridge University Press, 2023, pp. 295–408, https://doi.org/10.1017/9781009157926.005.

[15] Bistline, et al., Policy implications of net-zero emissions: a multi-model analysis of united states emissions and energy system impacts, Energy Clim. Change (2025), https://doi.org/10.1016/j.egycc.2025.100191.

[16] DOT, (Department of Transportation), Corporate Average Fuel Economy (CAFE) Standards, 2014. https://www.transportation.gov/mission/sustainability/corporate-average-fuel-economy-cafe-standards.
[17] J. Becker, M. Brown, M. Browning, Y. Cai, D.E. Goldfinger, J. McFarland, S. Paltsev, S.C.G. Weisberg, M. Yuan, US economy-wide decarbonization: sectoral and distributional impacts, Energy Clim. Change 6 (2025) 100181, https://doi.org/10.1016/j.egycc.2025.100181.
[18] T. Gao, S.S. Mai, C. Mousavi, M. Rossmann, J. Binsted, G. Bistline, M. Blanford, M. Browning, P. Fripp, M. Lamers, S. Muratori, J. Showalter, Weyant, Evolving electricity supply and demand to achieve net-zero emissions: Insights from the EMF-37 study, Energy Clim. Chang. 6 (2025) 100196, https://doi.org/10.1016/j.egycc.2025.100196.
[19] J.E.T. Bistline, Roadmaps to net-zero emissions systems: emerging insights and modeling challenges, Joule 5 (2021) 2551–2563, https://doi.org/10.1016/j.joule.2021.09.012.
[20] M. Binsted, E. Lochner, J. Edmonds, J. Benitez, J. Bistline, M. Browning, F.D. L. Chesnaye, J. Fuhrman, L. Göke, G. Iyer, K. Kennedy, P. Kyle, C. Lenox, H. McJeon, K. O'Keefe, P. O'Rourke, A. Prabhu, R. Sands, L. Sarmiento, S. Showalter, N. Victor, F. Wood, S. Yu, M. Yuan, Carbon management technology pathways for reaching a U.S. Economy-Wide net-Zero emissions goal, Energy Clim. Change 5 (2024) 100154, https://doi.org/10.1016/j.egycc.2024.100154.
[21] M.W. Melaina, C.S. Lenox, M. Browning, D.L. McCollum, O. Bahn, S. Ou, Modeling Hydrogen Markets: energy System Model Development Status and Decarbonization Scenario Results, Energy Clim. Change 5 (Dec) (2024) 100153, https://doi.org/10.1016/j.egycc.2024.100153.
[22] E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, E. Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, A. Swan, Net-Zero America: Potential Pathways, Infrastructure, and Impact, Princeton, NJ, 2020.
[23] Mai, T.T., Jadun, P., Logan, J.S., McMillan, C.A., Muratori, M., Steinberg, D.C., Vimmerstedt, L.J., Haley, B., Jones, R., Nelson, B., 2018. Electrification Futures Study: scenarios of Electric Technology Adoption and Power Consumption for the United States. Golden, CO (United States). https://doi.org/10.2172/1459351.
[24] A. Milovanoff, I.D. Posen, H.L. MacLean, Electrification of light-duty vehicle fleet alone will not meet mitigation targets, Nat. Clim. Change 10 (2020) 1102–1107, https://doi.org/10.1038/s41558-020-00921-7.
[25] C. Muratori, P. Ledna, C. Jadun, A. Hoehne, K. Yip, Podkaminer, Electrification pathways for U.S. passenger vehicles, Nat Sustain. Mobil. Transp. 2 (2025) 33, https://doi.org/10.1038/s44333-025-00052-6.
[26] M.B. Anwar, M. Muratori, P. Jadun, E. Hale, B. Bush, P. Denholm, O. Ma, K. Podkaminer, Assessing the value of electric vehicle managed charging: a review of methodologies and results, Energy Environ. Sci. 15 (2022) 466–498, https://doi.org/10.1039/D1EE02206G.
[27] A.F. Alarfaj, W.M. Griffin, C. Samaras, Decarbonizing US passenger vehicle transport under electrification and automation uncertainty has a travel budget, Environ. Res. Lett. 15 (2020) 0940c2, https://doi.org/10.1088/1748-9326/ab7c89.
[28] B. Girod, D.P. van Vuuren, S. Deetman, Global travel within the 2C climate target, Energy Policy 45 (2012) 152–166, https://doi.org/10.1016/j.enpol.2012.02.008.
[29] J. Sager, J.S. Apte, D.M. Lemoine, D.M. Kammen, Reduce growth rate of light-duty vehicle travel to meet 2050 global climate goals, Environ. Res. Lett. 6 (2011) 024018, https://doi.org/10.1088/1748-9326/6/2/024018.
[30] C. Yang, D. McCollum, R. McCarthy, W. Leighty, Meeting an 80 % reduction in greenhouse gas emissions from transportation by 2050: a case study in California, Transp. Res. D. Transp. Environ. 14 (2009) 147–156, https://doi.org/10.1016/j.trd.2008.11.010.
[31] J. Bistline, M. Browning, J. DeAngelo, D. Huppmann, R. Jones, J. McFarland, A. Molar-Cruz, S. Rose, S.J. Davis, Uses and limits of national decarbonization scenarios to inform net-zero transitions, Joule 8 (2024) 2721–2726, https://doi.org/10.1016/j.joule.2024.09.005.
[32] C. Bergero, G. Gosnell, D. Gielen, S. Kang, M. Bazilian, S.J. Davis, Pathways to net-zero emissions from aviation, Nat. Sustain. 6 (2023) 404–414, https://doi.org/10.1038/s41893-022-01046-9.
[33] D. Brownstone, T.F. Golob, The impact of residential density on vehicle usage and energy consumption, J. Urban. Econ. 65 (2009) 91–98, https://doi.org/10.1016/j.jue.2008.09.002.
[34] C.G. Hoehne, M.V. Chester, A.M. Fraser, D.A. King, Valley of the sun-drenched parking space: the growth, extent, and implications of parking infrastructure in Phoenix, Cities. 89 (2019), https://doi.org/10.1016/j.cities.2019.02.007.
[35] J. Moody, E. Farr, M. Papagelis, D.R. Keith, The value of car ownership and use in the United States, Nat. Sustain. 4 (2021) 769–774, https://doi.org/10.1038/s41893-021-00731-5.
[36] IEA, (International Energy Agency), 2021. Net-zero By 2050. Paris.
[37] M. Muratori, T. Mai, The shape of electrified transportation, Environ. Res. Lett. 16 (2021) 011003, https://doi.org/10.1088/1748-9326/abcb38.
[38] K.A. Perrine, K.M. Kockelman, Y. Huang, Anticipating long-distance travel shifts due to self-driving vehicles, J. Transp. Geogr. 82 (2020) 102547, https://doi.org/10.1016/j.jtrangeo.2019.102547.
[39] A. Pukhova, A.T. Moreno, C. Llorca, W.-C. Huang, R. Moeckel, Agent-Based simulation of long-distance travel: strategies to reduce CO2 emissions from passenger aviation, Urban. Plan. 6 (2021) 271–284, https://doi.org/10.17645/up.v6i2.4021.