Technology Executive Committee

08 March 2022

Twenty-fourth meeting

22-25 March and 28 March 2022 (TEC-CTCN Joint session)

Background paper on decarbonization technologies for sustainable road mobility

Background note

I. Introduction

A. Background

1. As per activity 3 of the of the thematic area Enabling environment and capacity-building of its updated workplan for 2019–2022, the TEC is to identify challenges and opportunities, including favourable market conditions, to strengthen enabling environments to enhance replicability and scalability of technologies for sustainable transport, including fostering public and private sector involvement. The expected deliverables of the activity are a background paper and a thematic dialogue to be delivered in 2022.

2. In the work leading to the publication of the technical paper on emerging climate technologies in the energy supply sector, the TEC taskforce on innovation produced a mapping of key emerging climate technologies in sectors with potential for climate change mitigation and adaptation, such energy supply, transport and agriculture, as well as technologies relevant to multiple sectors such as carbon removal and digital technologies. The task force eventually agreed to start working on emerging technologies in energy supply sector, while noting that other sectors may be considered for future work.

3. The technical paper on emerging technologies in the energy supply sector has the following objectives:

(a) Provides an overview of the technologies, their state of play, and potential climate change mitigation and adaptation impacts;

(b) Analyses the technologies' social, institutional, economic and business challenges and solutions related to their development and deployment, including new market access and social acceptability;

(c) Identifies ways for policymakers to effectively support the deployment of these technologies, especially using a systemic approach to innovation, commercialization, risk reduction, and lead and broad market uptake to normalize new sustainable supply and enabling technologies.

4. It is envisaged that the work on technologies for sustainable transport builds on similar objectives and approach to work to those of the technical paper on emerging technologies in the energy supply. This would allow the TEC to build on and benefits from lessons learned from existing work, while ensuring coherence of the overall work of the TEC.

B. Scope of the note

5. The note contains the proposed objectives of the work of the TEC on sustainable transport, the scope of the work, the timeline and deliverables for 2022, and an annex containing a background information on the state of play of technologies for sustainable transport.

C. Possible action by the Technology Executive Committee

6. The TEC will be invited to consider the background paper and provide guidance to the taskforce on further work on this issue, as appropriate.

II. Objective

7. The work on technologies for sustainable transport intends to analyse identify challenges and opportunities, including favourable market conditions, to strengthen enabling environments to enhance replicability and scalability of technologies for sustainable transport, including fostering public and private sector involvement.

8. The overall objective is to provide policymakers and other relevant stakeholders with a set of information that may help their decision making when defining national and/or regional strategies for accelerating the scale-up and diffusion of technologies for sustainable transport to help countries implementing mitigation actions to achieve the goals of Paris Agreement.

III. Scope

9. Transport sector has a critical role to play in achieving the Paris Agreement and Sustainable Development Goals (SDGs). In the NDC synthesis report, most Parties have indicated transport as priority sector for emission reduction. Transport sector is also identified as one of the priority sector of energy subsector for mitigation in countries' Technology Needs Assessment.

10. A mix of technology and policy options will be needed to close the gap between climate goals and the emissions. New technologies in transport sector and related infrastructures may offer comprehensive solutions to reduce emission.

11. Within the transport sector, road transport is one of the world's biggest carbon emission challenges and its emission continuously growing. It is estimated that transport sector is responsible for 24% of direct CO2 emissions from fuel combustion, about three-quarters of which are from road vehicles. Therefore, looking at the potential development, deployment and diffusion of technologies for sustainable road transport/mobility would represent an appropriate starting point of the work of the TEC in this sector.

12. As with work on emerging technologies in the energy supply, the work on technologies for sustainable transport will look at: (a) access to new markets; (b) social, institutional, economic and business preconditions, and (c) social acceptability of the technologies.

IV. Deliverables

A. Background paper

13. The overall purpose of the background paper is to identify policy options for further enhancing the development and transfer of advanced decarbonization technologies for sustainable road mobility.

14. The paper will look at selected advanced technologies and solutions for sustainable road mobility and to:

(a) Provide an overview of the technologies, their state of play, including information on when the technology may become commercially available, and potential climate change mitigation and adaptation impacts;

(b) Analyse social, institutional, economic and business challenges and solutions related to their development and effective deployment;

(c) Identify innovative policy options, opportunities and challenges for policymakers to effectively support the deployment of these technologies;

15. At a later stage the background paper could be converted into a full technical paper, should the TEC wish so (after TEC24).

B. Thematic dialogue

16. The overall purpose of the thematic dialogue is to gather global and regional experts to discuss and exchange views on policy options for further enhancing the development and transfer of advanced technologies and solutions for sustainable road mobility.

17. Specifically, the objectives of the thematic dialogue are to:

(a) Enhance the understanding on social, institutional, economic and business factors that affect the development and deployment of advanced technologies and solutions for sustainable road mobility;

(b) Identify policy options and actions that key stakeholders can take to facilitate effective deployment of advanced technologies and solutions for sustainable road mobility.

18. The thematic dialogues are intended to complement the analysis of this work. Depending on the timing of the thematic dialogue, the outcomes of the dialogue will be reflected as appropriate in the paper.

19. To maximise resource efficiency and to ensure high visibility, the thematic dialogue may be held in conjunction with the regional climate weeks in 2022 or at COP27.

C. Key messages and recommendations for the Conference of the Parties and the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement

20. While key messages and recommendations to the COP and CMA are currently not part of the deliverables of the work on this topic, it is not usual that the TEC produces such key messages and recommendations upon completion of its work. If desired by the TEC, key messages recommendation on emerging climate technologies for the COP and CMA will be produced, based on the findings of the paper and outcomes of the thematic dialogue.

V. Timelines

21. The table below shows a tentative timeline of the work:

#	Deliverables	Timeline
1	**Background paper** *Initial consideration at TEC 24 (March)* *Intersessional work of task force (April-August) 2021* *Final draft for consideration by TEC 25 in September* *Finalization after TEC 25*	March – September 2022
2	**Thematic dialogue** *Organized in conjunction with a regional climate week or COP27*	tbc 2022
3	**Key messages and recommendations to COP/CMA**	tbc 2022

Annex

Background paper on technologies and solutions for sustainable road mobility

By: Jonn Axsen

Simon Fraser University

Executive Summary

The transport sector needs to play a critical role in achieving global deep decarbonization targets, as it is responsible for 24% of direct CO2 emissions (from fuel combustion). About three-quarters of these emissions are from road vehicles. The International Energy Agency's Net Zero Emissions (IEA NZE) scenario assumes this sector needs to shift from over 90% fossil fuels to a mix dominated by low-carbon forms of electricity, hydrogen and biofuels – while also shifting travelers away from private vehicle usage. All this needs to occur while passenger travel doubles from 2020 to 2050, and goods-movement increases by 2.5 times. In line with these trajectories, at the 26th session of the Conference of the Parties to the UNFCCC (COP), 39 nations and 51 cities, states, and regional governments agreed to work towards achieving 100% zero-emissions vehicle (ZEV) sales by 2035 and no later than 2040.

The objective of this report is to identify and analyze the development, diffusion and impacts of advanced decarbonization technologies for road transport. It focuses on several technology categories that are expected to play an important role in the NZE, including: plug-in electric vehicles (PEVs),[1] hydrogen-powered fuel-cell electric vehicles (FCEVs),[2] advanced liquid biofuels, shared mobility modes and full vehicle automation. Insights are drawn from literature review, and each technology is assigned a Technology Readiness Level (TRL) from 1 (initial idea) to 11 (proof of stability), depicted in Table 1. Available data are considered for a variety of developed and developing countries.

Of these deep decarbonization technologies, the highest readiness is observed for light-duty PEVs and bus PEVs (TRL 10-11). Both of which also hold strong potential for substantially decreasing GHG emissions. Readiness is lower for FCEVs (TRL 8), which remain expensive for light-duty and heavy-duty applications, with very limited refueling infrastructure, as well as many remaining barriers to assure that most hydrogen produced to be "green". Readiness for advanced biofuels is also low (TRL 7-9). They have a potential advantage given that they can be used in blends with existing gasoline or diesel-based engines, but the development and market penetration of low-carbon ethanol and biodiesel has been limited in the last decade.

In terms of shifting travelers away from private vehicle ownership, several forms of shared mobility have made dramatic market progress in the last year, notably ride-hailing, car-sharing and micro-mobility. However, none of these modes has substantially displaced privately owned vehicles, nor do they demonstrate clear evidence of a net carbon benefit.

Finally, vehicle automation is in a relatively early state of development (TRL 4+). The potential future impacts are enormously uncertain, ranging from a doubling to halving of energy usage. Such technology would likely need to be carefully paired with low-carbon fuels, strong climate policy, and perhaps shared mobility to achieve the more optimistic automation scenarios.

The report ends by briefly summarizing several categories of climate policy: carbon and road pricing, market-oriented regulations, financial and non-financial subsidies, infrastructure provision and support for research and development. Strong policy mixes are needed to achieve deep decarbonization goals for road transportation, and to support the continued development of the technologies identified in this report. Given the evidence to date, these policy mixes are more likely to be successful if led by some combination of strong regulations and pricing.

[1] PEV is the broader category that includes battery-electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).
[2] These can also be called hydrogen fuel-cell vehicles or HFCVs.

Table 1 Key technology characteristics for low-carbon road transportation technologies

Technology	Sub-type	TRL	Penetration in 2020	Carbon impacts (well-to-wheel or lifecycle)	Role in IEA NZE 2050 Scenario
Plug-in electric vehicle (PEV)[a]	Light-duty	10-11	1-10% new market share in many countries; 75% in Norway	60-77% lifecycle cuts in North America and EU, 19-56% cuts in China/India	PEVs to be 60% of global sales by 2030, 90% by 2050
	Heavy-duty	8-11	<0.1% new market share for heavy trucks, 5-60% for buses	34-98% cuts in well-to-wheel emissions, 68% cuts in lifecycle emissions	PEVs to be 17% of sales by 2030, 68% by 2050
Hydrogen fuel-cell vehicle (FCEV) [a]	Light-duty	8	<0.1% new market share (25k vehicles)	26-40% lifecycle cuts in 2020 (mostly grey hydrogen), 76-80% lifecycle cuts with green hydrogen	FCEVs to be ~10% of global sales in 2050
	Heavy-duty	8	<0.1% new market share (5.5k buses, 3.5k heavy trucks)	60-97% well-to-wheel cuts with green hydrogen, 48% lifecycle cuts	FCEVs to be ~30% of global sales in 2050
Advanced biofuels[b]	Ethanol	7-8	About 3% of gasoline, but <0.1% of ethanol is advanced	Advanced ethanol up to 81% reductions; 2020 conventional mixes have impact ranging from negligible to 20% reduction	Advanced ethanol increases to 28% of ethanol by 2030, with stable total demand until 2050
	Biodiesel	9	About 16% of biodiesel is advanced	Advanced biodiesel from waste/residuals can cut GHG emissions 85-92%; conventional feedstocks can increase emissions	Advanced liquid biofuels meet 14% of transport energy by 2050
Shared mobility[c]	Ride-hailing	9-11	~3% US adults are regular users, much lower use of “pooled” service	Unclear; seems to be negligible GHG impact.	Could support “behaviour” shift: 20-50% away from private vehicles in 2030
	Car-share	9-10	Unknown, over 30 million members globally	Unclear; might reduce car-ownership	Could support “behaviour” shift
	Micromobility	9-10	Unknown, available in 650 cities	Unclear; negligible impact, or might increase GHG emissions.	Could support “behaviour” shift
	Mobility as a Service	8	Very low, dozens of projects globally.	Unclear; might contribute to 3-15% GHG decrease	Could support “behaviour” shift
Fully automated vehicles (FAVs)	Light/heavy	4+	Demonstration only	Highly uncertain; impacts could halve or double GHG emissions; could be 20-33% lower GHGs if shared rather than private	Not addressed

[a] For vehicles, where possible *new market share* is reported, which is defined as the percentage of sales in 2020. That is different from the *stock market share*, which is the percentage of vehicles on the road.
[b] For biofuels, the market share is the percentage of fuel in that category (ethanol or biodiesel).
[c] For shared mobility categories, market share is more difficult to define. Numbers are reported according to availability, which can include percentage of “regular users” or “members”, or availability of programs.

Acronyms

ASEAN	Association of Southeast Asian Nations
BEV	battery-electric vehicles
BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	Conference of the Parties
DC	direct current
gCO_2e/MJ	grams of carbon dioxide equivalent per megajoule
EU	European Union
FAV	fully automated vehicle
GEF	Global Environment Facility
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions and Energy us in Technologies model
H_2	hydrogen
HDRD	hydrogenation-derived renewable diesel
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
IEA	International Energy Agency
ILUC	indirect land-use change
IRENA	International Renewable Energy Agency
kW	kilowatt
kWh	kilowatt-hour
LCA	life-cycle analysis
MaaS	Mobility-as-a-Service
MJ	megajoule
MJ/km	megajoules per kilometer
MW	megawatt
NZE	Net Zero Emissions
PEV	plug-in electric vehicle
PHEV	plug-in hybrid vehicle
PKM	passenger-kilometers travelled
R&D	research and development
SAE	Society of Automotive Engineers
TEC	Technology Executive Committee
TKT	tonne-kilometers travelled
TRL	Technology Readiness Level
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
V2G	vehicle-to-grid
V2H	vehicle-to-home
VKM	vehicle-kilometers travelled
WTW	well-to-wheels

Introduction

The Paris Agreement clearly states the importance of GHG mitigation goals to achieve 1 holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;. It also identifies the important role of technological innovation in promoting economic growth while achieving climate and sustainable development goals. This report focuses on the potential roles of several innovations in the transport sector. Transport is responsible for 24% of direct CO_2 emissions (from fuel combustion), about three-quarters of which are from road vehicles (IEA, 2020b). Despite decades of investment in low-carbon fuels and technologies, most developed countries remain locked-in to the dominance of privately-owned, fossil fuel powered vehicles (International Energy Agency, 2019). At the same time, vehicle ownership rates are quickly increasing in many developing countries such as China, India and Russia.[3] Without the addition of strong climate policy mixes, global transport emissions are expected to grow further (Axsen et al., 2020).

Following the Paris Agreement, many countries are committing to reach net-zero GHG and net-zero CO_2 emissions by 2050 in order to achieve holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;. Such goals will require enormous transitions in the transport sector. According to the International Energy Agency's (IEA) Net Zero Emissions (NZE) scenario, the energy mix that powers the transport sector will need to shift from over 90% fossil fuels in 2020 to be mostly replaced by a mix with 45% electricity, 28% hydrogen-based fuels and 16% bioenergy fuels in 2050 (IEA, 2021e). At the same time, transportation demand is forecast to grow rapidly in the NZE. From 2020-2050, global demand for passenger travel is expected to double,[4] with an increase in the global light-duty fleet from 1.2 billion to 2 billion vehicles. Freight or goods-movement is expected to increase by 250% from 2020 to 2050.[5]

For these reasons, many nations and regions are pursuing goals to substantially increase zero-emissions vehicle (ZEV) sales as one component of deep decarbonization. Most recently at the 26th UN Climate Change Conference (COP26), 39 nations and 51 cities, states, and regional governments agreed to work towards 100% ZEV sales by 2035 and no later than 2040 (GOV.UK, 2021). As of late 2021, one country has committed to 100% ZEVs of new cars by 2025 (Norway), eight countries have committed to the goal by 2030 (Denmark, Iceland, Ireland, Israel, the Netherlands, Singapore, Slovenia and the UK), and five countries by 2035 (Cabo Verde, China, Japan, the UK, Canada, and the EU) (IEA, 2021a). In 2019, The UN and Global Environment Facility (GEF) have also launched the Global Electric Mobility Program to assist 27 developing countries in shifting to ZEVs.[6]

Clearly there is a need for enhanced development of low-carbon transportation technology, and a corresponding need for strong climate and innovation policies to support them. COP-26 Decision 1/CP.26 emphasizes the need for enhanced financing and technology transfer for low-carbon technology.[7] The objective of this report is to identify and analyze the development, diffusion and impacts of advanced decarbonization technologies, including plug-in electric vehicles (PEVs), hydrogen-powered fuel-cell electric vehicles (FCEVs), advanced liquid biofuels, shared mobility modes and vehicle automation. The specific objectives are to:

1. Provide an overview of the technologies and their state of play, including information on their technology readiness and potential climate change mitigation impacts;
2. Briefly summarize some social, institutional, economic and business opportunities related to their development and effective deployment; and
3. Identify innovative policy options, opportunities and challenges for policymakers to effectively support the deployment of these technologies.

The Summary in Section 9 provides further details of priority items that could be expanded in next steps, including: deeper analyses of technology barriers and opportunities, especially for developing nations, more in-depth evaluation of climate policies, and consideration of additional low-carbon technologies.

[3] https://www.globaldata.com/higher-vehicle-ownership-across-developing-nations-comes-at-a-cost-says-globaldata/
[4] Measured as passenger-kilometers travelled or PKM.
[5] Measured as tonne-kilometers travelled or TKM.
[6] https://www.thegef.org/newsroom/press-releases/un-led-partnership-accelerate-electric-mobility-shift-27-countries
[7] https://unfccc.int/sites/default/files/resource/Overarching_decision_1-CP-26_0.pdf

Scope

2.1 Details of technology sector

Road transportation is typically split by purpose into passenger travel and goods-movement (or freight). It can also be split by vehicle type, including light-duty vehicles, sometimes labelled "cars", though this category often includes a high proportion of light-duty truck, and notably sport-utility vehicles.[8] "Heavy" or heavy-duty vehicles tends to include "trucks", often split into heavy trucks and medium trucks, [9] as well as buses and various vocational vehicles. In terms of GHG emissions from road transport, there is a fairly even split between light- and heavy-duty vehicles. Global GHG emissions have been rising for all modes of road transport, but are increasing at an especially high rate for heavy-duty vehicles used for freight (IEA, 2020b).[10]

This report does not focus on two-wheelers and three-wheelers, though these make up larger markets in some developing countries, in part because they are more affordable than four-wheel road vehicles (Rajper and Albrecht, 2020), while potentially reducing or avoiding congestion. Section 6.3 on micro-mobility does briefly address sharing of bikes, e-bikes and e-scooters.

To help categorize the range of mitigation solutions and policies, this report considers the categories used by policymakers in California and elsewhere in North America (Sperling and Eggert, 2014). Mitigation measures in the transport sector are broken into three categories:

1. switching to low-carbon fuels, reducing grams of CO_2-equivalent per megajoule or gCO_2e/MJ,
2. improving vehicle efficiency, reducing megajoules per km or MJ/km, and
3. reducing vehicle travel, fewer vehicle kilometers travelled or VKM, either from mode switching or reduced travel activity.

This report is focused on technology innovation in the first category, notably fuel switching from conventional fossil fuels to electric, hydrogen and advanced liquid biofuels. Though, electric and hydrogen fuel-cell vehicles also offer improvements in efficiency (the second category, MJ/km). The third category, VKM reduction, is also flagged as important in the IEA NZE scenario.

This three-part framework also facilitates comparison of policies (Section 8). Pricing mechanisms are technology neutral and can induce a wide variety of mitigation actions. Regulations tend to target specific pathways to fuel-switching or efficiency, such as standards for low-carbon fuels, ZEVs or improved vehicle efficiency. Similarly, purchase incentives tend to focus on one or two low-carbon technologies, such as PEVs or FCEVs. Policies aimed at improved shared mobility might target reduced VKM, but they may also seek other societal goals such as improved equity and reduced traffic congestion.

2.2 Methodological approach

A literature review was conducted to achieve the objectives stated in section 1, with over 130 documents cited. Details from the IEA NZE scenario report have been especially helpful (IEA, 2021e). The NZE project conveys the potential scale of change needed for each deep-decarbonization technology in the global transport sector, while integrating input from a wide range of transportation experts and stakeholders. This report also draws from several other IEA reports,[11] as well as reports by the International Council for Clean Transportation (ICCT), notably their recent work in lifecycle analysis for vehicle GHG emissions in the US, Europe, China and India.[12]

Documents were also identified through searches in various scholarly databases, notably Elsevier, as well as targeted searches in the leading journals in this research are, such as: *Transportation Research Part A: Policy and Practice*, and *Transportation Research Part D: Transport and Environment*, *Nature Energy*, and *Nature Climate Change*. These searches were used to identify the latest high-quality, peer-reviewed papers for each technology. Where necessary, grey literature reports were also consulted, especially to collect some details that tend to be proprietary, such as usage of ride-hailing and car-share programs.

[8] https://www.iea.org/commentaries/global-suv-sales-set-another-record-in-2021-setting-back-efforts-to-reduce-emissions
[9] Medium-duty vehicles are defined differently by context, and often grouped with heavy-duty vehicles—which is done in this report also.
[10] https://theicct.org/a-world-of-thoughts-on-phase-2/
[11] Including: *Global EV Outlook 2021*, https://www.iea.org/reports/global-ev-outlook-2021
Global Hydrogen Review 2021, https://www.iea.org/reports/global-hydrogen-review-2021
Tracking Report: Transport Biofuels, https://www.iea.org/reports/transport-biofuels
Tracking Report: Trucks and Buses, https://www.iea.org/reports/trucks-and-buses
[12] https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/

To assess technology development, each deep-decarbonization technology category is classified using the Technology Readiness Level (TRL) scale. This scale was initially developed by NASA with levels from 1 to 9. The IEA later expanded it to 11 levels as shown in Table 2 (IEA, 2021b). This report uses the IEA scale to ensure consistency with previous publications of the Technology Executive Committee (TEC) on emerging climate technologies. Table 1 in the Executive Summary summarizes the main takeaway points for each technology in this report.

Table 2 Technology Readiness Levels and policy implications (using IEA and NASA definitions; Adapted from: (Bataille and Li, 2021; IEA, 2019))

Broad stage	TRL	Narrow stage
Conceptual or Research phase	1	Initial idea: basic principles observed or defined
	2	Application formulated: technology concept and application formulated
	3	Concept needs validation: experimental proof of concept, solution needs to be prototyped and applied
Small prototype (development phase)	4	Early prototype: technology proven in test conditions, validated in lab
Large prototype (Development phase)	5	Large prototype: technology/components validated in relevant environment (conditions to be deployed)
	6	Full prototype at scale: technology proven at scale in relevant environment (conditions to be deployed)
Demonstration (Deployment phase)	7	Pre-commercial demonstration: technology working in expected conditions (operational environment)
	8	First-of-a-kind commercial: commercial demonstration, full-scale deployment shown in final form
	9	Commercial operation in relevant environment: system is commercially available, needs evolutionary improvement to stay competitive
Early Adoption	10	Integration needed at scale: solution is commercial but needs further integration efforts
Mature	11	Proof of stability: predictable growth

Most of the technologies reviewed in this report are in the TRL 8-11 range. These scores indicate that the technologies are commercially available to some degree, but they differ in terms of realized market share. This report interprets these levels as follows:

- TRL 8: commercial demonstrations, but with very low market share (<0.1% of new sales or fuel mix).
- TRL 9: commercially available, but only in very early market form (achieving 1% market share or less).
- TRL 10: a technology with market share in the range of 1% to 10%, which is in the “early adopter” segment of the market (Rogers, 2003).
- TRL 11: a technology with greater than 10% new market share, which is a sign of entering the “mainstream” market segment (Rogers, 2003).

There may be a range of TRL levels for a given technology, due to either differences in readiness across sub-categories of the technology, or differences in market penetrations across different countries. The achievement of full maturity (TRL 11) that is independent of policy support can be difficult to prove for low-carbon technologies. Generally, the success of deep decarbonization technologies is tightly linked to existing climate and innovation policy. For example, the very high PEV new market share observed in Norway has been supported by over a decade of strong policy (Figenbaum, 2017). It is difficult to anticipate what would happen with the removal of those polices.

This report also summarizes available information regarding the carbon impacts of each innovation category. There are three broad perspectives on carbon impacts for road vehicles:

- Tailpipe emissions reports only what is emitted by the vehicle during operation. Under this perspective, PEVs and FCEVs are considered to be zero-emissions. This measure ignores any other carbon impacts, such as those produced during extraction or refining of fossil fuels, generation of electricity, or production of biofuels or hydrogen.
- Well-to-wheel (WTW) emissions considers the full impacts of the fuel, including production biofuels and hydrogen, and the generation of electricity. WTW is often measured in grams of CO_2-equivalent per megajoule (gCO_2e/MJ).
- Full lifecycle analysis (LCA) considers WTW emissions associated with the fuel and the vehicle. Vehicle impacts typically include the production, operation and disposal of the vehicle and all its components.

This report summarizes available evidence on WTW and LCA impacts as available. For some technologies and fuel feedstocks, there are vast literatures of emissions impacts with high uncertainty and wide ranges, especially by region. There are several WTW and LCA databases that are more well-known for both research and policy, such as the Greenhouse gases, Regulated Emissions and Energy us in Technologies (GREET) model at Argonne National Labs.[13]

Plug-in electric vehicles

The term ZEV typically includes vehicles powered by grid electricity or hydrogen. This section includes battery-electric vehicles (BEVs) that are powered only by electric motors, and plug-in hybrid electric vehicles (PHEVs) that can be plugged in or powered by an internal-combustion engine. The term plug-in electric vehicle (PEV) typically refers to both BEVs and PHEVs.[14] This summary of PEVs is split between light-duty vehicles and heavy-duty vehicles. This preliminary report focuses more on PEV technology in general, and not on the specifics of different battery chemistries such as lithium-ion and solid-state batteries.[15]

3.1 Light-duty plug-in electric vehicle (TRL 10-11)

The IEA consider the recent growth in light-duty PEV sales to be "on track" for the NZE scenario (IEA, 2021a). Light-duty PEVs are consistent with levels TRL 10-11—at TRL 10 for most developed countries, and TRL 11 for the few countries with high enough penetration to demonstrate the mainstream potential of PEVs. However, market success has been mostly in North America, Europe and China, with negligible sales of four-wheel PEVs in most developing countries.

3.1.1 Technology background

While designs vary across different makes and models, the novel components of a BEV are the large, advanced battery and electric motor, while a PHEV also includes an ICE. For PEVs sold in 2020, the global average battery capacity was 55 kilowatt-hours (kWh) for BEVs, and 14 kWh for PHEVs (IEA, 2021c)—with considerable variation across makes and models. In North America and Europe, BEVs from 2020 have electric driving ranges as low as 175km to over 500km for the long-range Tesla Model 3. PHEV ranges tend to vary from 25km to 75km electric or "charge-depleting" driving range, typically in addition to 500 to 800km of "charge-sustaining" driving range using the ICE. The global weighted 2020 average for light-duty BEV ranges was about 350km in 2020, and 50km for PHEVs (IEA, 2021c).

Globally, there were 370 different PEV car models available for sale in 2020, which is a 40% increase from 2019 (IEA, 2021c). Even more varieties of PEV models are being announced by most automakers, with some announcing plans to cease their production of light-duty ICE vehicles in the coming decades, such as GM's plan for 2035,[16] and Honda's goal for 2040.[17]

Over the last decade, advanced automotive battery performance has continued to improve, including increasing energy and power density, which translates to longer range vehicles with quicker acceleration. Lithium-ion battery packs prices have seen vast reductions in price, falling from $1,200/kWh in 2010 to $140/kWh in 2020, and $132/kWh in 2021 (BloombergNEF, 2021). However, further technology development and cost reductions will be needed to help meet 100% ZEV sales goals.

Charging for PEVs can be categorized by location and speed. The majority of charging events occur at home or work locations, which tend to be "slow" charging, categorized as charging power below 22 kilowatts (kW). Public charging includes both slow and "fast" charging that is 22 kW or above. Faster charging includes direct current (DC) fast chargers that operate at 50 kW to 250 kW and can recharge a BEV battery by 80% in about 15 to 45 minutes. The number of publicly accessible chargers increased from 2019 to 2020 by 45%, reaching 1.3 million units. 30% of these were fast chargers (IEA, 2021c). The total numbers of public chargers in 2020 is highest in the China, followed by Europe, then the US (IEA, 2021c). Only a small fraction of slow and fast chargers are in the rest of the world, though there are relatively high ratios of public chargers to PEV stock in Korea, Chile, Indonesia, South Africa and Japan (IEA, 2021c). The NZE assumes further increases in global public chargers from 1.3 million in 2020 to 40 million in 2030 and 200 million in 2050.

There is continued development of several forms of "smart charging" technology, which seek to coordinate PEV charging behavior to better complement the grid (IRENA, 2019). Smart charging could help to lower electricity costs, and even reduce GHG emissions if used to help integrate intermittent, renewable forms of electricity (Wolinetz et al., 2018). These smart charging technologies are beyond the scope of this report but could be explored further in next steps.

---

[13] https://greet.es.anl.gov/

[14] Note that a conventional hybrid (hybrid-electric vehicle or HEV) does not plug in to charge, and thus does not use grid electricity. Conventional hybrids are not included in this report.

[15] Note that PEV battery manufacturing is concentrating among a few companies in Asia, notably CATL (China), LG (Korea), Panasonic (Japan) and BYD (China). See: https://elements.visualcapitalist.com/ranked-top-10-ev-battery-makers/

[16] https://www.caranddriver.com/news/g35562831/ev-plans-automakers-timeline/

[17] https://global.honda/newsroom/news/2021/c211013beng.html

3.1.2 Market penetration

In 2020 there were over 10 million light-duty PEVs on the road, making up about 1% of stock, and 3% of new vehicle sales (ICCT, 2021a; IEA, 2021a). Sales rates varied widely across countries, with the leaders being Norway (75% of new market share being PEVs), Sweden (35%), the Netherlands (28%), Germany (14%), the UK (11%), and France (11%) (IEA, 2021c). Comparing larger markets, Europe leads with 10% new market share in 2020, followed by China (6%) and the US (2%). Only a small fraction of PEV sales and stock are outside these three regions. In 2020, PEV sales declined in Japan and New Zealand. Most developing countries have negligible PEV sales, though India and Chile are increasing their PEV sales targets and policy support (IEA, 2021c). Sales of electric two-wheelers and three-wheelers have been dominated by Asia, though there is also increasing support in African countries such as Uganda and Kenya.[18]

3.1.3 Carbon impacts

The GHG impacts of PEVs vary according to a wide range of factors including vehicle type, drive cycle, electricity grid mix, timing of charging, battery production and the vehicle that is being replaced. However, it is generally clear that PEVs can lead to substantial GHG emissions reductions.

Numerous studies using LCA and WTW perspectives indicate that PEVs can cut emissions by 60% to 95% compared to conventional ICE vehicles (Ambrose et al., 2020; Hoekstra, 2019; Kamiya et al., 2019). The ICCT conducted a recent full LCA of the GHG emissions from PEVs in 2020 and in 2030, comparing impacts in Europe, the US, China and India (ICCT, 2021b). The study considers the full GHG impacts of production and consumption of fuels and electricity, manufacturing of vehicles and batteries, and lifetime maintenance. The 2030 GHG reductions tend to be more substantial due to the development of lower-carbon electricity grids, among other expected changes. In summary, results show that over their lifetime, medium-sized BEVs can reduce GHG emissions relative to a comparable ICE in each region as follows:

- Europe: 66-69% in 2020, 74-77% in 2030
- United States: 60-68% in 2020, 62-76% in 2030
- China: 37-45% in 2020, 48-64% in 2030
- India: 19-34% in 2020, 30-56% in 2030

The GHG impacts of PHEVs are more uncertain because it is unknown what percentage of driving will be powered by grid electricity versus gasoline in the ICE. The 2020 medium-sized PHEVs are found to offer GHG benefits as follow, relative to an ICE (ICCT, 2021b):

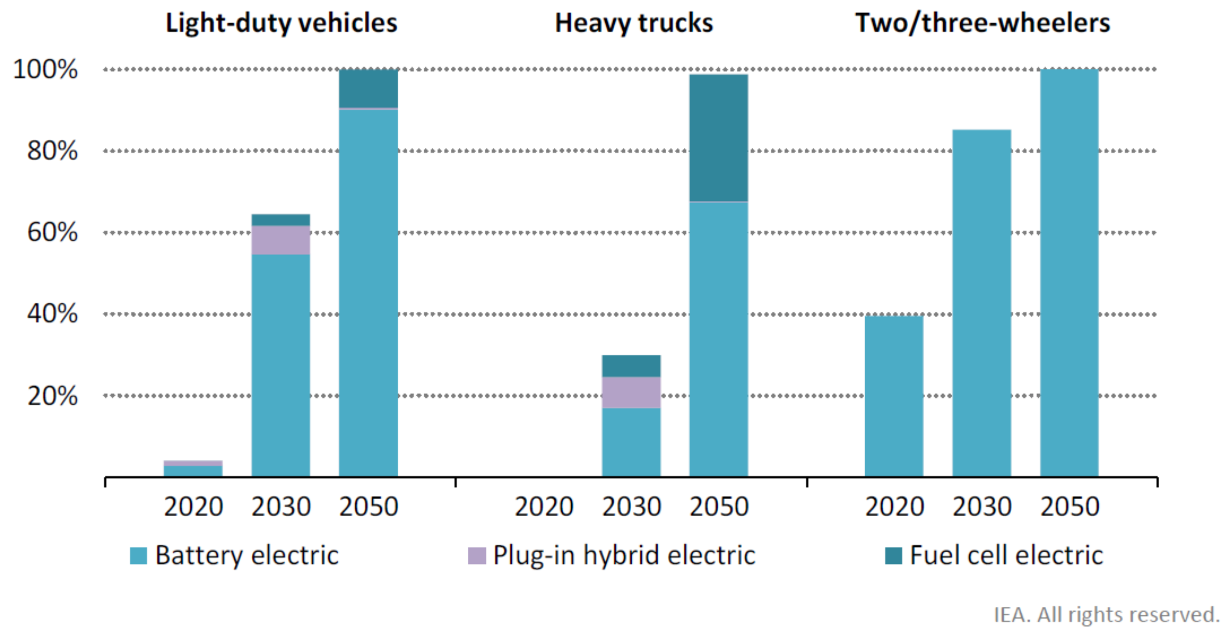
- Europe: 25-27% reductions
- United States: 42-46% reductions
- China: 6-12% reductions.

3.1.4 Role in Net Zero Emission scenario

To move towards deep decarbonization goals, the IEA NZE scenario assumes that PEVs will need to make up 61% of global light-duty vehicle sale by 2030—with most developed countries attaining around 100% new market share between 2030 and 2035 (IEA, 2021e). As shown in Figure 1, the NZE assumes that the PHEVs would make up about 5% of 2030 sales, and a negligible portion of sales in 2050. To assure that the decarbonization potential of PEVs are maximized, the NZE assumes a massive scale up of renewable sources of electricity, quadrupling the amount of installed capacity of solar and wind from 2020 levels by 2030 (IEA, 2021e).

[18] https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/2021_event04

Figure 1: IEA Net Zero Emissions Scenario assumptions on penetration of battery electric, plug-in hybrid and fuel-cell electric vehicles (Source: IEA, 2021e)



Sales of battery electric, plug-in hybrid and fuel cell electric vehicles soar globally

3.2 Heavy-duty plug-in electric vehicles (TRL 8-11)

The IEA categorizes the "trucks and buses" sector as "not on track" for deep decarbonization goals due to the lack of progress in vehicle efficiency, GHG reductions, and ZEV uptake (IEA, 2021g). That said, the TRL of PEVs varies widely by truck category and region—though it is generally lower than that of light-duty PEVs. Buses are categorized as TRL 10-11, heavy-duty trucks as TRL 8-9, and medium-duty trucks as TRL 8-10.

3.2.1 Technology background

Relative to light-duty passenger travel, there is less research and policy focus on heavy-duty and freight vehicles,[19] despite their continued importance in global GHG emissions. This heavy-duty category can be broken down into a range of sub-categories, including passenger buses, medium- and heavy-duty freight trucks. There is also a diverse "other" category that includes "vocational" vehicles such as garbage, bucket, concrete mixer and sweeper trucks. As one point of reference, the IEA breaks down GHG emissions from this broad sector into 55% from heavy trucks, 27% from medium trucks, and 18% from buses (IEA, 2021g).

One challenge for decarbonization of heavy-duty vehicles is that this sector may be more complicated and diverse than passenger vehicle. Specifically, there is a wider range of vehicle types, loads, and usage profiles, such as short-haul versus long-haul freight, and various vocational uses for trucks. For example, studies suggest that BEVs might be more appropriate for shorter distance vehicles, such as delivery trucks, garbage trucks, and short-haul freight, whereas FCEVs might be better suited for long-haul trucks (Hammond et al., 2020; IEA, 2021e; Liimatainen et al., 2019; Moultak et al., 2017).

Based on analysis of current and announced models from 2020 to 2023, the electric driving ranges vary as follows (IEA, 2021c):

- Buses vary from 50-650 km, being 290km average,
- Heavy freight trucks vary from 100-700km, being 400km on average, and
- Medium freight trucks vary from 100-450km, with 275km being the average.

In 2021 there were about 245 different electric bus models available for sale globally, along with 120 electric medium-duty trucks, and 50 electric heavy-duty truck models (IEA, 2021c). In the US as one example, the number of heavy-duty models is

[19] Reasons for this lack of research may include lack of availability of private and proprietary data, as well as lack of political will due to the perceived link between goods-movement and economic growth.

expected to grow 2.5 times from 2020-2023.[20] Numerous manufacturers are planning additional heavy-duty BEV models, including announcements made by Volvo, Daimler (Freightliner), Nikola, MAN, Scania and Tesla.[21]

A major challenge of this sector is that larger and heavier vehicles require higher capacity batteries and higher power charging. Two potential technology solutions are worth considering. First is the development of "megachargers" that recharge at a rate of 1 megawatt (MW) or more that could facilitate long-haul trucking needs by more quickly charging up the large batteries. Megacharger development efforts are underway by numerous stakeholders, including CHAdeMO[22] and the China Electricity Council, the CHarIN initative,[23] and Tesla (IEA, 2021c). A second solution is the use of overhead catenaries to charge heavy-duty vehicles while in motion,[24] especially in long-haul operations (Schwerdfeger et al., 2021). For example, catenaries are being tested in several projects in Germany (by Siemens Mobility and SPIL Powerlines Germany), and one project in the UK has roads with 3.4-20km stretches of catenaries (IEA, 2021g).

3.2.2 Market penetration

As noted, PEV market penetration varies widely by truck category, and region. The main sub-categories are summarized as follows:

- **Buses**: About 85,000 electric buses were registered in 2020, making up 3% of global bus sales (ICCT, 2021a). Most of these are in China (78,000), followed by smaller numbers in Europe (2100 total, making up 4% of new registrations), and North America (580 total) (IEA, 2021c). There is now a global stock of about 600,000 electric buses. The countries with the highest new market shares of electric buses include the Netherlands (69%), China (23%), Norway (17%), Sweden (10%), and the UK (6%) (ICCT, 2021a). Market shares are fairly low outside China and the EU, including Canada (1.7%), the US (0.6%), India (0.4%) and Japan (0.1%). PEV sales are negligible in most developing countries.
- **Heavy-duty trucks:** The global heavy-duty PEV truck market reached sales of 7,400 in 2020 (a 10% increase from 2019), contributing to a global stock of 31,000 vehicles (IEA, 2021c). PEVs made up less than 0.1% of global heavy truck sales (ICCT, 2021a). The vast majority of new sales were again in China (6,700), followed by those in Europe (450) and the US (240) – the latter two representing less than 1% of sales (IEA, 2021c). PEV sales were negligible outside of these countries.
- **Medium-duty trucks:** PEVs made up 0.5% of medium truck sales in 2020, with 6.5% new market share in Germany, 3.4% in the Netherlands, 2.8% in the UK, and 1.3% in China (ICCT, 2021a). PEV sales were negligible outside of China and the EU.

3.2.3 Carbon impacts

As with light-duty vehicles, the GHG impacts of medium- and heavy-duty PEVs vary with the sources of electricity, as well as usage patterns. Here are examples of study results from three developed countries:

- Canada: heavy-duty freight BEVs can cut WTW GHG emissions by 34-98% (compared to diesel) for short- and long-haul applications, depending primarily on the drive cycle and electricity source (Lajevardi et al., 2019).
- US: a study of LCA GHG emissions accounting for manufacturing batteries and charging stations found that heavy-duty BEVs only perform slightly better than diesel trucks (Sen et al., 2017). However, GHG reductions can be as high as a 63% reduction with a cleaner electricity grid.
- Norway: heavy-duty BEVs can cut LCA GHG emissions by 68%, when including vehicle and drivetrain manufacturing (Booto et al., 2021).

As with light-duty vehicles, the GHG reductions are likely to be smaller in magnitude in China, India, and other developing countries that have more carbon-intensive electricity grids.

3.2.4 Role in Net Zero Emission scenario

In the NZE scenario, PEVs make up 25% of global heavy truck sales by 2030, 50% by 2035 and around 70% by 2050 (Figure 1). The stock of electric buses is expected to follow a more ambitious trajectory, making up 60% of sales in 2030, and 100% by 2050. As with light-duty vehicles, the IEA assumes that the PHEVs would make up about 5% of 2030 sales, with negligible sales in 2050. By that time, PHEVs would be fully replaced by BEVs and FCEVs.

[20] https://www.fleetowner.com/emissions-efficiency/article/21164837/us-heavyduty-zev-models-to-grow-250-by-2023
[21] https://www.autoweek.com/news/green-cars/a36506185/electric-big-rig-semi-trucks/
[22] CHAdeMO is a Direct Current (DC) charging standard for PEVs, developed by the CHAdeMO Association. https://www.chademo.com/about-us/what-is-chademo/
[23] https://www.charin.global
[24] Catenaries are overhead powerlines that a PEV can attach to in order to power or recharge the vehicle.

3.3 Opportunities for plug-in electric vehicles

There are numerous socio-economic opportunities to further develop the PEV market. Three opportunities are noted here. First, countries could more widely implement the strong policies already demonstrated by PEV leaders that showed early and sustained policy support, including Norway, California (US), and Quebec (Canada) (Lemphers et al., 2022). PEV sales in these regions have been driven by combinations of strong regulations, incentives, and pricing mechanisms. These policies are further described in Section 8. More countries globally would likely increase PEV sales by emulating these types of strong policies (Melton et al., 2020). Relatedly, the heavy-duty sector should also make more use of these same policies that have proven to be effective for the light-duty sector, notably regulations requiring ZEV sales and lower-carbon fuels (Hammond et al., 2020).

Second is to take advantage of opportunities in the global south to further develop PEV markets, especially as car ownership rates are quickly increasing (Sovacool et al., 2022). In some cases, total cost of ownership might be lower for BEVs, for example with a 30% cost reduction compared to conventional vehicles in Ghana (Ayetor et al., 2021). Research on four cities in Africa (Johannesburg, Kigali, Lagos and Nairobi) suggest that PEV deployment in these regions could take advantage of increasing vehicle sales in general, as well as the growing markets for low cost e-bikes and e-scooters (Sovacool et al., 2022). Two- and three-wheelers present an opportunity for low-cost electrification, with less impact to electricity grids due to smaller batteries (IEA, 2021c). Though, electric two/three-wheelers are only likely to provide a carbon benefit if they are replacing or offsetting the use or purchase of fossil-fuel powered ICE vehicles.

Third, countries and stakeholders could make better use of "smart charging" programs that aim to optimize the timing of PEV charging to better complement the electricity grid. Such programs can improve GHG reductions if designed to complement the availability of intermittent sources of renewable energy. Studies find that such programs could cut the GHG emissions of PEV usage by up to 20% in Beijing (Chen et al., 2022), or 50% in Germany (Kacperski et al., 2022). Smart charging programs can also potentially reduce the electricity prices resulting from increased use of renewable forms of electricity (Wolinetz et al., 2018). Relatedly, more research is needed on battery "second use", where batteries that are no longer suitable for vehicle usage might still provide a helpful load management service to electrical grids.

Fuel cell electric vehicles (FCEVs)

Hydrogen is a combustible gas that is used in a variety of chemical and refinery processes. It can also be used for other end-uses such as direct process heating and transportation. While it is possible to power an ICE with hydrogen, the current focus for transportation is on fuel cell electric vehicles (FCEVs) that use fuel cells to convert hydrogen to electricity. The electricity then powers the vehicle via an electric motor.

Although FCEVs emit no tailpipe emissions, the WTW GHG impact depends primarily on the source of energy used to produce the hydrogen. In recent years, a common terminology has developed as follows (Bataille and Li, 2021):

- Black hydrogen is the most carbon-intensive form, produced from coal via steam methane reformation.
- Grey hydrogen is produced from natural gas via steam methane reformation, and tends to be the lowest cost production method.
- Blue hydrogen is produced from natural gas as with grey hydrogen, but using carbon capture and storage (CCS) to capture about 90% of the CO_2 emissions, which are typically stored underground.
- Green hydrogen uses electrolysis to transform the electricity produced by wind and solar generation into a storable fuel, and thus can be low-carbon. Green hydrogen can also utilize excess intermittent renewable energy that might be costly to store otherwise. Green hydrogen has been recently reviewed elsewhere by the UNFCCC TEC, and rated at TRL 8+ (Bataille and Li, 2021).

The IEA NZE scenario assumes that all forms of hydrogen will make up 28% of transport fuels in 2050, while green hydrogen will increase from 5% of hydrogen sources in 2020 to 63% in 2050 (IEA, 2021e).

4.1 Light-duty fuel cell electric vehicles (TRL 8)

4.1.1 Technology background

As with PEVs, FCEVs are considered to be a type of ZEV due to their lack of tailpipe emissions. Hydrogen is stored on-board, and then converted to electricity using the fuel-cell, which powers an electric motor. Light-duty FCEV models in 2021 include the Honda Clarity, Toyota Mirai, and Hyundai Nexo, which have driving ranges around 500-700km and take several minutes to refuel.[25] While most light-duty automakers are focused on PEVs, Toyota and Hyundai remain committed to FCEVs. For example, Toyota is planning to release hydrogen-powered versions of the Prius and Corolla in 2023.[26]

FCEVs face several technology barriers in the light-duty market. Manufacturing costs and purchase prices remain high, with double the total cost of ownership compared to conventional ICE vehicles (Li and Taghizadeh-Hesary, 2022). These high costs are in part due to very low production volumes, and the high cost of hydrogen (Li and Taghizadeh-Hesary, 2022; Whiston et al., 2022). That said, there has been progress. From 2008 to 2020, the cost of automotive fuel cells has decreased by 70% (IEA, 2021d). FCEVs also benefit from the decreasing costs of advanced batteries and electric motors.

A further challenge is that FCEVs cannot be refueled at home and thus rely on the deployment of hydrogen fueling stations, which in turn relies on the production of hydrogen. In 2020 there were about 540 hydrogen fueling stations globally, which is a 15% increase from the previous year (IEA, 2021c). The vast majority of these stations are in Europe, Japan, China, the US, and Korea—with only a few in other countries. The IEA NZE assumes an increase to 18,000 stations by 2030 and 90,000 by 2050.

4.1.2 Market penetration

FCEVs first became commercially available in 2014. However, they are categorized as TRL 8 because they remain very low in availability, stock, and new market share. The global stock of light-duty FCEVs in 2020 was about 25,000 vehicles, 29% of which are in Korea, 27% in the US, 24% in China, and the rest mostly in Japan and Europe (IEA, 2021c). FCEV sales and stock are negligible outside these countries. In 2020 the total stock of FCEVs doubled from 2019, mainly due to Korea doubling its total stock (IEA, 2021c).

4.1.3 Carbon impacts

As noted, the GHG emissions impacts vary strongly with the source of hydrogen—though generally FCEVs can yield net reductions. The ICCT's analysis of light-duty FCEVs found that the medium-sized FCEVs used in 2020 cut GHG emissions by 26-40% compared to conventional gasoline vehicles across the tested regions: North America, Europe, China and India. These present day sources are dominated by "grey" hydrogen (ICCT, 2021b). Using green hydrogen results in LCA GHG emissions that are 76%–80% lower than conventional gasoline vehicles. These LCA emissions are somewhat higher than BEVs using the same renewable electricity due to the energy-intensive nature of converting renewable electricity to hydrogen, and then back to electricity (ICCT, 2021b).

4.1.4 Role in Net Zero Emission scenario

As depicted in Figure 1, the NZE scenario assumes that FCEVs make up a few percent of light-duty sales in 2030, and up to 10% by 2050 (IEA, 2021e).

4.2 Heavy-duty fuel cell electric vehicles (TRL 8)

4.2.1 Technology background

Heavy-duty FCEVs are based the same principles as light-duty models and have similar needs for hydrogen production and refueling infrastructure. Some studies suggests that FCEVs might be better suited for heavy-duty applications, in part because FCEVs can store more energy for heavy-duty vehicles than BEVs. For example, the IEA NZE assumes that FCEVs will be more competitive than BEVs for heavy trucks with daily ranges that exceed 450km (IEA, 2021e). However, there are still substantial barriers to heavy-duty FCEV uptake. In particular, total cost of ownership for heavy-duty FCEVs is calculated to be triple compared to conventional ICE vehicles (Li and Taghizadeh-Hesary, 2022).

Current FCEV trucks include the Hyndai Xcient cargo truck, which has a 400km range and requires 8-20 minutes to refuel. Plans for further heavy-duty models have been announced by Daimler, Renault, Nikola, Volvo and other manufacturers (IEA, 2021d). As noted for light-duty FCEVs, the fueling infrastructure remains limited at about 540 hydrogen fueling stations globally in 2020.

[25] https://afdc.energy.gov/vehicles/fuel_cell.html
[26] https://www.forbes.com/sites/peterlyon/2021/08/29/toyota-to-launch-hydrogen-powered-prius-and-corolla-in-2023/?sh=5bbce65a2fa1

4.2.2 Market penetration

Heavy-duty FCEVs are rated as TRL 8 because they are commercially available in some markets, but have very low penetration to date. In 2020, there were about 5,500 FCEV buses and 3,500 FCEV trucks on the road. The vast majority of these are in China, which has 94% of the buses and 99% of the trucks (IEA, 2021c).

4.2.3 Carbon impacts

Heavy-duty FCEVs can offer similar climate benefits as for their light-duty counterparts, especially if green hydrogen is used. A WTW analysis indicates that the impacts of heavy-duty vehicles powered by grey hydrogen can range from a 4% increase to a 65% decrease in GHG emissions, depending on drive cycle and drivetrain technology (Lajevardi et al., 2019). The use of green hydrogen more clearly leads to deep cuts of 89-97% compared to heavy diesel trucks (Lajevardi et al., 2019). A Norway-based study similarly finds that heavy-duty FCEVs can cut lifecycle GHG emissions by 48% when including GHG impacts from vehicle and drivetrain manufacturing (Booto et al., 2021). A China-based study indicates that green-hydrogen powered FCEVs heavy trucks and buses can reduce WTW emissions by 60-77% (Li and Taghizadeh-Hesary, 2022).

4.2.4 Role in Net Zero Emissions scenario

Heavy-duty FCEVs are expected to play more of a decarbonization role in future years. In the IEA NZE scenario, FCEVs are assumed to make up about 5% of heavy-duty sales in 2030, and 30% of sales in 2050 (Figure 1). Supporting this projection, several other studies suggest that there could be a fairly even split between BEVs and FCEVs in the heavy-duty vehicle sector of a deep decarbonization world. Two different Canada-based modeling studies find that when achieving 80% GHG reduction goals for the transport sector with competition among ZEVs, there is a split in 2050 between hydrogen- and electricity-powered heavy-duty vehicles (Hammond et al., 2020; Lepitzki and Axsen, 2018). In particular, FCEVs are simulated to make up 74% of new heavy freight truck sales in 2050 (Lepitzki and Axsen, 2018).

4.3 Opportunities for fuel cell electric vehicles

Further expansion of light-duty and heavy-duty FCEV markets will have to address the main barriers: high purchase price and lack of refueling infrastructure. Any success in FCEV sales to date are highly dependent on generous purchase subsidies, especially in China (Li and Taghizadeh-Hesary, 2022). Continued purchase subsidies can help in the short-term, though long-term success will need to drastically increase production levels and achieve technology breakthroughs in order to bring down manufacturing costs.

Further FCEV development would benefit from the continued activity of international alliances to help with R&D (Li and Taghizadeh-Hesary, 2022). In particular these efforts and alliances need to work together to identify key technology areas to increase the performance and affordability of FCEV components (Cullen et al., 2021). There is some optimism for future progress. One study finds that while the future is highly uncertain, hydrogen experts tend to forecast positive trends for FCEVs, including a three-fold decrease in fuel-cell production costs from 2020-2035 (Whiston et al., 2022).

Continued development of FCEVs will also benefit from ZEV-supportive policies that include similar incentives for FCEVs as are already available for BEVs. This includes the purchase subsidies noted above as well as support for fueling infrastructure. Further, regulations that require ZEV sales and low-carbon fuels provide a further signal for the private sector to invest in FCEVs and green hydrogen.

Advanced Biofuels

5.1 General biofuel background

Transport or liquid biofuels tend to be categorized into two pools. Ethanol can be blended with or replace gasoline, and made up 59% of transport biofuel consumption in 2020 (IEA, 2021f). Biodiesel can be blended with or replace diesel, and made up 41% of 2020 transport biofuel consumption.[27] From 2013 to 2019, developing countries produced about 40% of global liquid biofuels (Subramaniam and Masron, 2021).

In road transportation, most liquid biofuels are currently consumed through blending at low percentages in gasoline or diesel fuel at a rate of 5% overall, and typically at a maximum of 10% or less (IEA, 2021f). Flex-fuel vehicles are designed to run on higher biofuel blends, such as an E85 blend that is up to 85% ethanol, or in some cases a pure biofuel (unblended). “Drop-in”

[27] Natural gas can also be derived from biological sources (bio-methane, renewable natural gas), which could also be used to power road vehicles. This source is not addressed in the current report.

fuels are still under development and offer the advantage of being used in high shares or even unblended in engines designed for gasoline or diesel, without requiring engine modification.

Because liquid biofuels can be made from a variety of feedstocks, their GHG emissions and other sustainability impacts can vary widely. In the last two decades, energy policies in some countries required or supported biofuel blending, without distinguishing between sources. For example, uptake of corn ethanol in the US was helping to reduce petroleum use but did not reduce lifecycle GHG emissions relative to gasoline (Farrell et al., 2006). Further, conventional biofuel crops are likely to compete for land with food crops. For these reasons, there is now a major distinction between conventional and advanced biofuel feedstocks.

Conventional biofuels use food-based crops, compete for land with food, and can have a variety of lifecycle GHG emissions impact—including slight or negligible reductions or even substantial increases. In 2020, 93% of liquid biofuels were produced from three types of conventional food-based crops: corn, sugarcane and soybeans (IEA, 2021e).

In contrast, advanced bioenergy is defined by the IEA as fuels that (IEA, 2021e, p205):

i. deliver significant lifecycle GHG reductions compared to the fossil fuels they are replacing,
ii. are produced from non-food crop feedstocks,
iii. do not directly compete for land with food or feed crops, and
iv. do not cause other adverse sustainability or biodiversity impacts.

Feedstocks for advanced biofuels include waste streams and residues (from agriculture and industry), woody residues and short-rotation woody crops, and other feedstocks that do not compete with food (IEA, 2021e). Biofuels can also be produced with carbon capture and storage (CCS),[28] which addresses GHG goals but not necessarily other sustainability goals. In the NZE scenario, biofuels produced with CCS is assumed to account for about 10% of bioenergy consumption in 2050. Other advanced biofuels use developing technology such as cellulosic ethanol and biomass-to-liquids.[29] The production costs of advanced biofuels are still double to triple those of fossil fuels, but could decline by one-quarter or more by 2030 (IEA, 2020a). Advanced feedstocks made up only 7% of biofuels produced in 2020, mostly produced from used cooking oil and waste animal fat. The NZE scenario targets an increase to 45% share of biofuels by 2030.

Global demand for liquid biofuels has increased by 5% per year from 2010 to 2019. After an 8% demand reduction due to Covid-19 pandemic in 2020, further growth is expected (IEA, 2021f). In 2020, biofuels accounted for only 3% of global transport fuels, and the IEA assesses biofuel development as currently "not on track" to meet decarbonization goals (IEA, 2021f). According to the NZE scenario, the consumption of biofuel will need to increase 14% per year from 2020 to 2030, to reach almost 15% blending share in fossil fuels by 2030, and 41% blending share in 2050 (IEA, 2021e). However, biofuels are expected to play a limited role in road transportation past 2030, where BEVs and FCEVs dominate in the NZE. Most advanced biofuels would instead be used for aviation and shipping. With that in mind, biofuels would still make up about 10% of fuel energy usage for heavy-duty trucks in 2050.

5.2 Advanced ethanol (TRL 7-8)

5.2.1 Background and market penetration

Ethanol is produced by fermenting biomass. Conventional ethanol is made from food energy crops such as corn, wheat, sugar beet, sugarcane, barley and rye. Ethanol is mostly produced from corn in places such as the US, China, Argentina, Bulgaria, India and several African countries (Subramaniam and Masron, 2021). In Europe, ethanol production has a more even split between corn (38% of the ethanol mix), wheat (30%) and sugar beet (19%) (ICCT, 2021b). Bolivia, Uruguay, Mexico and Brazil mostly produce ethanol from sugarcane (Subramaniam and Masron, 2021). Southeast Asian countries such as Thailand and the Philippines can produce ethanol from cassava and sugar cane (Kumar et al., 2013). Generally, there are significant feedstock resources in Latin American and Southeast Asian countries that can be further developed (IEA, 2021f). Notably, Brazil is one the world's leading countries in ethanol production (Subramaniam and Masron, 2021).

Advanced ethanol is produced using wastes and residues and non-food energy crops, using the definition noted above. Feedstocks include cellulose and hemicellulose (fibrous material that is abundant in plant matter), such as wheat straw, woody raw materials and agricultural residues (ICCT, 2021b; IEA, 2021e). The production of advanced ethanol is still in early stages of development, with relatively negligible global penetration in most markets due to the high cost (TRL 7-8). The share of wheat straw as an advanced form of ethanol has achieved 4% share of ethanol in Europe in 2020, and is expected to increase to 13% in 2030 (ICCT, 2021b).

[28] Also known as bioenergy with carbon capture and storage or BECCS.
[29] Sometimes called "second generation" biofuels.

Regardless of feedstock, ethanol can be blended into gasoline and used by conventional gasoline ICEs with no modification, typically at rates of 5% in Europe and China, 10% (and now up to 15%) in the US and Canada, and 5-20% in India (ICCT, 2021b). Blending up to 85% ethanol (E85) can be done with flex-fuel vehicles, which exist in significant number in a few countries, notably the US (21 million vehicles), Canada (1.6 million), Brazil (30 million) and Sweden.[30] However, many of these flex-fuel vehicles are refueled mostly or exclusively with conventional gasoline rather than the E85 blend, especially in North America. One drawback of ethanol is that gasoline and flex-fuel vehicles tend to achieve lower fuel economy with ethanol than gasoline for two reasons: i) ethanol has lower energy density than gasoline, and ii) conventional gasoline engines are designed to run optimally with gasoline rather than ethanol.

5.2.2 Carbon impacts

The lifecycle impacts of ethanol vary substantially by feedstock, agricultural and production method, and region. The calculation of lifecycle impacts is uncertain as well, especially the incorporation and quantification of indirect land-use change (ILUC). Ethanol use in the US and China is dominated by conventional corn feedstocks, which yields lifecycle GHG reductions around 18-22% when accounting for ILUC (ICCT, 2021b). Analysis of light-duty vehicles in Europe shows that the GHG impacts of conventional ethanol can vary by feedstock, with a 24% reduction in GHG emissions from corn, 54% from sugar beets, and 56% from sugar cane. On the other hand, wheat-based ethanol can range from a 4% increase to 8% reduction in GHG emissions, and barley/rye causes an 11% increase in emissions. Wheat straw, an advanced ethanol feedstock, can yield 81% reductions in LCA GHG emissions.

Relatively less analysis is conducted on the lifecycle impacts of biofuels produced in developing countries, especially in Africa (Karkour et al., 2021). One WTW study of Latin America indicates that corn ethanol produced in Argentina can reduce GHG emissions by 37% compared to gasoline, while switchgrass ethanol produced in Argentina, Brazil, Colombia and Guatemala can reduce emissions by 66-74%.[31]

5.2.3 Role in Net Zero Emissions scenario

In the NZE scenario, total ethanol consumption is assumed to increase by 38% from 2020 to 2030, and then to contract for 2040 and 2050 (IEA, 2021e). Among ethanol fuels, the proportion of advanced ethanol is assumed to increase from <0.1% in 2020 to 27% of ethanol demand in 2030. Another 23% is assumed to be conventional ethanol with CCS in 2030, at a magnitude that stays consistent until 2050.

5.3 Advanced biodiesel (TRL 9)

5.3.1 Background and market penetration

Conventional biodiesel is produced using the fatty acid and methyl esters (FAME) route (transesterification) from food oil crops, such as rapeseed, palm, soybean, flax, sunflower, mustard and coconut. The proportion of feedstocks vary by region; in Europe, the biodiesel mix includes 52% rapeseed oil and 20% palm oil (ICCT, 2021b). Biodiesel is largely produced from palm and soybean oil in Brazil, Argentina, Uruguay and Indonesia (Subramaniam and Masron, 2021). Indonesia and Malaysia are the two largest producers of palm oil, and both countries are aiming to increase their biodiesel production (Kumar et al., 2013)

Advanced biodiesel uses non-food feedstocks such as waste cooking oil, fish oil, algae oil, animal fats, and potentially cellulosic material as well—which generally requires more advanced production methods such as Fischer-Tropsch.[32] Advanced forms of biodiesel made up 16% of the global biodiesel mix in 2020 (IEA, 2021f). As one example, Europe's 2020 biodiesel feedstock mix include 17% used cooking oil and 5% cooking fats (ICCT, 2021b).

Biodiesel can be blended into diesel and used in diesel vehicles with no engine modification, though performance can be compromised at higher blends. Common blending rates are 7% in Europe and 5% in India (ICCT, 2021b). Biodiesel blending rates in the US include 2%, 5%, and 20% and 100%, though warranties for many vehicles will not cover blends of 20% or higher. Use of 100% biodiesel generally requires engine modifications. Hydrogenation-derived renewable diesel (HDRD) is emerging as a form of "drop-in" diesel that can be produced by fat or oil-based biodiesel feedstocks, while maintaining a

[30] https://en.wikipedia.org/wiki/Flexible-fuel_vehicle
[31] https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/04-03_MENDES_SOUZA.pdf
[32] https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/alternative-fuels/biofuels/biodiesel/3509

chemical composition that is the nearly identical to diesel and allowing up to 100% blends with no engine modifications. HDRD production has developed in Singapore for export to countries such as the US and Canada.[33]

5.3.2 Carbon impacts

As with ethanol, the lifecycle impacts of biodiesel vary substantially by feedstock. As one example, analysis of Europe demonstrates that conventional biodiesel can substantially increase GHG emissions, such as when made from rapeseed oil (22% increase in GHG emissions intensity), palm oil (180% increase), soybean oil (120% increase) and sunflower oil (11% increase) (ICCT, 2021b). However, use of advanced biodiesel made from used cooking oil, animal fats and other residual sources can reduce GHG emissions by 85-92%. One WTW study of Latin America indicates that biodiesel produced from soybean oil can reduce GHG emissions by 79% in Argentina and 68% in Brazil, while palm-oil based biodiesel produced in Colombia can reduce emissions by 84%.[34]

5.3.3 Role in Net Zero Emissions scenario

The NZE scenario assumes that biodiesel will play a role in lowering heavy-duty truck emissions in the 2020s, before BEVs and FCEVs dominate in the 2030s and 2040s. The total consumption of biodiesel is expected to increase by over 3.5 times from 2020 to 2030. Among the biodiesel pool, the proportion of advanced biodiesel is assumed to increase from 16% in 2020 to 58% in 2030 (with about a third of the advanced biodiesel using carbon capture), and to over 90% of biodiesel used in 2050 (IEA, 2021f). Similarly, a modeling study of deep decarbonization in Canada found that biofuels would make up 43% of energy demand by freight transportation in 2050 when ambitious climate policies in place, including a low-carbon fuel standard (Lepitzki and Axsen, 2018).

5.4 Opportunities for advanced biofuels

A major opportunity for biofuel development is for policymakers to send a clear signal for research and development to focus on advanced, notably low-carbon forms of ethanol and biodiesel. There is still potential to develop lower-cost production methods for low-carbon biofuels, including cellulosic ethanol, HDRD, and biofuel with CCS (or BECCS). There is also considerable potential for further development of low-carbon biofuels in developing countries, notably Latin America and Africa, provided that various sustainability goals are also achieved.[35]

Existing policies are increasingly helping in this direction by specifically requiring reductions in the lifecycle carbon intensity of these fuels. Examples include Europe's "Fit for 55", California's low-carbon fuel standard (LCFS), the US Renewable Fuel Standard, Canada's Clean Fuel Standard (CFS), India's ethanol blending mandate, China's latest 5 year plan, and Latin America's RenovaBio (IEA, 2021f). Research shows that such policies can drive reductions in carbon intensity. For example, following implementation of the low-carbon fuel standard, from 2011-2019 the lifecycle of carbon intensity of ethanol used in California declined by 29% and the carbon intensity of biodiesel fell by 36% (California Air Resources Board, 2020). On the plus side, numerous studies find that low-carbon fuel standards enjoy the highest levels of citizen support among transportation climate policies (Long et al., 2020; Rhodes et al., 2017).

Relatedly, there is opportunity for more comprehensive coverage and integration of these policies, to better avoid "leakage" or "shuffling" effects. Leakage occurs where low-emissions biofuels are sent to regulated regions, while higher-emissions biofuels are sent to unregulated regions, reducing any net global GHG benefit from policy (Bento et al., 2015).

Shared mobility

Shared mobility includes a variety of modes that move away from the dominance of privately-owned, single occupancy passenger vehicles. The broad concept can be split between:

i. the sharing of vehicles, including car-sharing, bike-sharing, and scooter-sharing; and
ii. the sharing of rides, including ride-hailing and car-pooling.

Numerous studies argue that in addition to the enormous transitions in fuels and efficiency needed to meet net zero CO_2 goals, "behavior changes" will also be needed (Brand et al., 2021; IEA, 2021e). In transportation, this usually refers to reductions in the rates of vehicle ownership and vehicle usage to achieve mitigation in the VKM reduction category noted in Section 2.1. The NZE scenario assumes that such behavior changes account for 4% of cumulative emissions reductions by 2050. In 2030,

[33] https://afdc.energy.gov/fuels/emerging_hydrocarbon.html
[34] https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/04-03_MENDES_SOUZA.pdf
[35] https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/04-03_MENDES_SOUZA.pdf

45% of these changes occur in transportation, including a shift of about 20-50% of passenger trips in larger cities from single-occupancy passenger vehicles towards shared mobility, public transit and active travel (IEA, 2021e). These behavioral changes are also assumed to reduce car ownership in 2050, where the proportion of single-car households fall from 35% to 20%, and two-car households fall from 13% to 5% (IEA, 2021e).

This section summarize several existing and emerging forms of shared mobility and their potential roles in deep decarbonization: ride-hailing, car-sharing, micromobility, and Mobility-as-a-Service (MaaS). The net GHG impacts of these modes is largely variable and unclear, depending on: i) the carbon intensity of the mode being replaced, ii) the impact on vehicle ownership, and iii) the impact on overall VKM. Some researchers pay particular attention to the importance of "pooling", where a shared mobility mode that uses vehicles, namely ride-hailing and car-sharing, are only likely to reduce GHG emissions if they are used for trips that "pool" multiple passengers strangers to increase overall vehicle occupancy (Sperling, 2018).

6.1 Ride-hailing (TRL 9-11)

Ride-hailing is defined as an app-based platform that allows users to hail a ride from a professional driver. Uber and Lyft are the most well-known service providers on most countries (Shaheen, 2018). Uber is now available in more than 10,000 cities in 71 countries worldwide.[36] It can be important to distinguish between:

i. individual-use ride-hailing, that is, taking a trip alone or with friends/acquaintances; and
ii. pooled ride-hailing where a trip is shared among two or more strangers, aside from the driver. These trips generally require multiple pick-up and drop-off points and have more potential to lead to VKM reduction.

Ride-hailing began to enter some markets around 2010, and by 2018 15% of adults in the US have used it (and 21% of adults in major cities)—though "regular" users may only represent 3% of the total population (Rodier, 2018). Penetration of ride-hailing has been slower in most European countries, though it is increasing in China, with higher reported usage than in the US.[37] Ride-hailing is having a range of positive and negative impacts on many other developing countries, such as Pakistan (Shah and Hisashi, 2021) and Mexico (Eisenmeier, 2018).

The environmental impacts of ride-hailing are generally unclear, as it is difficult to identify the different orders of impacts. Some US studies indicate that ride-hailing can reduce car-ownership (Rodier, 2018), especially among frequent users of ride-hailing (Wang et al., 2021). However, studies in the US and China indicate that ride-hailing can increase overall vehicle travel (Schaller, 2017). Further, ride-hailing usage typically substitutes for public transit, active travel and taxi usage (Clewlow and Mishra, 2017; Shaheen, 2018; Shi et al., 2021). While net impacts are uncertain, it is suggested that ride-hailing is leading to a slight increase in GHG emissions in the US (Rodier, 2018). Another US study finds that ride-hailing usage on weekends may help to reduce GHG emissions, which is also when there is a higher proportion of "pooled" ride-hailing (Wang et al., 2022). However, heavier weekday usage may increase GHG emissions (Wang et al., 2022). A simulation study of Paris, France, finds that while ride-hailing usage can lead to GHG reductions, about two-thirds or more of the benefit is cancelled out by rebound effects (Coulombel et al., 2019). Rebounds occur when reductions in travel costs and travel times can lead to users switching away from transit, driving longer distances and relocating their residences further from the urban center.

6.2 Car-sharing (TRL 9-10)

Car-sharing involves a traveler paying an hourly and/or mileage-based rate to pick up a vehicle, use it, and return it somewhere (Cervero et al., 2007).[38] Car-share programs vary in a number of ways. In particular, parking can be station-based or free-floating, and trip structure can be one-way or two-way (Lempert et al., 2019). Peer-to-peer (P2P) car-sharing is an emerging form that allows individuals to rent out their personal vehicles (Sopjani et al., 2019).

While smaller car-share programs have existing for decades, substantial growth has occurred in recent years. From 2006 to 2018, the number of global members has increased from around 350,000 to over 30 million, and the number of car-share vehicles has increased from around 11,000 to almost 200,000 (Shaheen and Cohen, 2020). Global membership increased by a factor of 10 from 2014 to 2018 (Shaheen and Cohen, 2020). As of 2020, carsharing programs have been documented in 47 countries, with over two-thirds of members in Asia, and about 20% in Europe (Shaheen and Cohen, 2020). There has also been support for car-share programs in other developing countries, notably Brazil (Rio de Janeiro), Mexico (Mexico City), Turkey (Istanbul) and India (Delhi).[39]

[36] https://www.uber.com/global/en/cities/
[37] https://www.weforum.org/agenda/2017/05/hailing-a-ride-china-leads-the-way-on-mobility-apps/
[38] Car-sharing is typically called a "car club" in the UK and parts of Europe.
[39] https://www.smartcitiesdive.com/ex/sustainablecitiescollective/car-sharing-picking-speed-developing-world/152996/

The net societal impacts of car-sharing programs are uncertain, though it is often considered as a pathway to reduce vehicle ownership (Baptista et al., 2014; Firnkorn and Müller, 2011). One study of 11 European cities finds that car ownership was reduced in each city due to the car-share program, where each car-share vehicle can replace several or up to 20 private cars (Jochem et al., 2020). An earlier US-based car-share study indicates that participation in a car-share program reduced the average number of cars per household from 0.47 to 0.24 (Martin et al., 2010).

However, it is difficult to separate causality and self-section effects in car-share research. It is likely that at least some car-share members were planning to reduce their car ownership before joining the program. Such a transition might also have included the traveler moving their residence to a denser neighborhood. In car-share research, it is often unclear if the program caused the identified reduction in VKM or vehicle-ownership for members. Worryingly, car-sharing can also promote private vehicle use among those that otherwise would use transit or active travel (Kent and Dowling, 2013). One recent study of US young adults finds that car-share usage is positively associated with transportation GHG emissions, though it may also complement usage of public transit (Wang et al., 2022).

6.3 Shared micro-mobility (TRL 9-10)

Micro-mobility follows similar principles to car-sharing, but includes the sharing of bikes, e-bikes and e-scooters. There is the added variation that some such programs are "dockless", with no particular parking or storage space at all (Yin et al., 2019). While shared micro-mobility was largely suspended during Covid-19 lockdowns, since then 270 cities have relaunched operations services (IEA, 2021c). As of February 2021, 650 cities are documented with shared micro-mobility services (IEA, 2021c). Shared e-scooters have over-taken shared dockless bikes in Europe, Central Asia and North America, though shared bikes are more popular in East Asia and Pacific countries (IEA, 2021c). Average trip distances on e-scooters have increased by 25% compared to before the pandemic (IEA, 2021c). There has also been a recent increase in the use of swappable batteries, which allows operators to quickly replace depleted e-scooters and e-bikes with fully charged batteries.

Again, the emergence of micro-mobility holds the potential for GHG emission reductions if it is replacing higher-carbon modes and supporting, rather than displacing, public transit and active travel (Bucher et al., 2019). Bike-sharing in particular is hoped to inspire more travelers to take up active-travel, though again, the evidence is unclear (Hosford et al., 2018). As with car-sharing, the important question is: what mode is being replaced? Also, one study considers lifecycle emissions from micro-mobility, including vehicle, fuel, infrastructure and operational services. The authors find that shared e-scooters and shared e-bikes can emit more gCO_2 per passenger km travelled (PKM) than public transit, personal bikes, and privately owned e-bikes and e-scooters (Reck et al., 2022).

Impacts vary by study and region, but findings generally suggest that micromobility is not inducing substantial GHG reductions. As key examples, mostly from the US:

- US: a recent statistical study of US travel data finds that bike-share usage is not associated with an increase or decrease in travel GHG emissions (Wang et al., 2022).
- Nashville, US: shared e-scooters can reduce bus ridership by 0.08% on a given weekday (Ziedan et al., 2021).
- Chicago, US: shared e-scooters have reduced bike-sharing usage by 20% (Yang et al., 2021).
- Washington, DC, US: shared e-scooters are often substituting for transit and bikeshare usage due to time savings. Though, in some cases, e-scooters can complement transit, where 10% of e-scooter trips connected with the city's Metrorail system (Yan et al., 2021).
- Zurich, Switzerland: e-scooters could increase gCO2 per PKM by 92%, when accounting for the modes they substitute for. E-bikes could similarly increase GHG emissions by 43% (Reck et al., 2022).

More research is needed to assess the current and future potential impacts of micro-mobility, especially in developing countries.

6.4 Mobility-as-a-Service (TRL 8)

The concept of Mobility-as-a-Service (MaaS) aims to advance the potential complementarity of public transit and shared mobility. The hope is to increase the usage of both modes, and ultimately to reduce private vehicle ownership and usage (Matyas and Kamargianni, 2018). MaaS can be defined as defined as follows: with a single payment and streamlined user experience, travelers can get from origin to destination through some combination of public transit, ride-hailing, car-share and/or micro-mobility modes. Public transit lines are often seen as the "backbone" of a MaaS system, where the shared mobility modes could mitigate the "first mile" or "last mile" problem associated with commuter rail systems (Yan et al., 2021). The term MaaS is thought to have been coined in 2014 in Finland, and is now being explored in pilots around the world, notably Europe (Arias-Molinares and García-Palomares, 2020). The International MaaS Alliance maintains a list of dozens of

MaaS initiatives and projects across Europe, including Sweden, the UK, Germany, France and Spain, as well as Canada, the US, Taiwan, Singapore and Australia.[40]

A 2020 review of 59 MaaS studies indicates that evidence regarding its costs and benefits are uncertain (Arias-Molinares and García-Palomares, 2020). As with other forms of shared mobility, MaaS would only induce GHG emission reductions if it increases the use of low-carbon modes of travel in place of higher-carbon modes—notably more active travel and shared mobility in place of single-occupancy vehicle usage. While some literature suggests that MaaS could reduce private car usage and reduce GHG emissions, there is limited evidence (Labee et al., 2022). In one pilot study in Sydney (Australia), the vehicle travel (VKM) of MaaS users significantly dropped over time, although many participants continued to use cars (Hensher et al., 2021). Simulations using data from Amsterdam (the Netherlands), demonstrate that MaaS could reduce emissions by 3-4% in a "conservative" scenario, 14-19% in a "balanced" scenario, and 43-54% in an "optimistic" scenario (Labee et al., 2022).

Less research is focused on MaaS for developing countries. In one survey of travellers in Manila (Philippines) survey, 84% of respondents say they would use a MaaS app, and 61% of potential users stated they would increase their use of public transport if MaaS was available (Hasselwander et al., 2022).

6.5 Opportunities for shared mobility

One clear opportunity for shared mobility modes is to put more emphasis on GHG emissions reductions, both for program design and research. The main avenue for decarbonization is to make sure that uptake of the shared mobility mode is substituting for higher carbon modes of travel, and reducing private vehicle ownership and usage. For the sharing of light-duty vehicles via ride-hailing and car-sharing, there needs to be more push and support for pooled usage (Sperling, 2018). Another avenue is to assure that any shared vehicle usage is electric, where some stakeholders are proposing policies that incentivize or require ride-hailing or car-sharing to use BEVs, which would improve the carbon benefit (Hall et al., 2021). More generally, countries seeking further deployment of these shared mobility modes can benefit from enacting legislation that facilitates uptake, ideally in a manner that maximizes GHG benefits – such as Finland's Act on Transport Services.[41]

Finally, improved consumer research can help to understand how to attract more consumers, and different consumer groups, to shared mobility programs. As one example, a survey in Ghana found that car-share programs are more attractive to travellers with higher pro-environmental and pro-technology attitudes, as well as those dissatisfied with existing transit services (Acheampong and Siiba, 2020)

Fully automated vehicles (TRL 4+)

This report uses the term fully automated vehicles (FAVs), while acknowledging that the terms autonomous, self-driving and driverless vehicles are often used differently or even synonymously (Sperling et al., 2018b).[42] There are a number of frameworks used to define different levels of automation. This report uses the 5-level system by the Society of Automotive Engineers (SAE, J3016) which specifies Levels 1 and 2 as including automated features that are already available in the market, e.g., adaptive cruise control, self-parking, and lane changes. Level 3 automation can fully drive itself, though the driver needs to be ready to take over on short notice by having their hands on the wheel, and eyes on the road. A FAV is in the realm of Level 4 and 5, which requires no driver attention. A Level 4 AV can drive in most but not all possible conditions, e.g., extreme weather or a traffic emergency). A Level 5 FAV can drive itself in all possible conditions.

FAVs are not currently available for sale,[43] and most of the plans announced by automakers and other companies over the last decade have missed their self-imposed deadlines. More recently, General motors has announced plans for privately owned FAVs to be available by the mid-2020s.[44] Further, numerous freight operators and heavy-duty vehicle manufactures are actively working on automation technology, especially for long-haul trucking (ICCT, 2018). To date, FAVs remain in a prototype state that is still being validated in relevant operating conditions, namely on road, with real traffic conditions (TRL 4+).

Widespread FAV uptake could profoundly impact society in a number of ways, including travel patterns, vehicle and housing choices, and overall environmental impacts (Milakis et al., 2017). There is enormous uncertainty about if and when FAV deployment may occur for passenger travel and freight, whether it will be deployed more for private or shared vehicles, and the

---

[40] https://maas-alliance.eu/maas-in-action/ (Note: it is not clear that all listed project meet the definition of MaaS provided in this report.)
[41] https://www.lvm.fi/-/improvements-to-everyday-mobility-through-act-on-transport-services-984789
[42] Research and policy may also differentiate "connected" and "automated" features of a vehicle. This report focuses only on automation in general, though the next steps could look more closely at connected vehicles.
[43] Note that Tesla's "Autopilot" feature does not yet qualify as fully-automated, as it is not SAE Level 4 or 5.
[44] https://www.wired.com/story/you-own-self-driving-car/

ultimate magnitude and direction of societal impacts. Several optimization modeling studies have shown the dramatic potential for positive impacts resulting from best case conditions: a fleet of shared, automated, electric vehicles. As examples:

- This combination could cut GHG emissions per PKM by 87-94% compared to conventional vehicles, even with substantial increases in vehicle travel, average speed and vehicle size (Greenblatt and Saxena, 2015).
- Viegas et al. (2016) use detailed travel data from Lisbon, Portugal to show that such a fleet could meet travelers' requirements with 97% fewer vehicles, 95% less parking space, 37% fewer vehicle km, and much lower operating costs.
- Alonso-Mora et al. (2017) find that 98% of New York taxi demand could be met with 15-20% of the vehicles (if shared and automated) with no projected negative service impact.

However, there is a much wider range of potential energy and GHG impacts, which includes large potential for negative impacts. Wadud et al. (2016) provide a particularly useful analysis of boundary conditions for FAV, finding that calculations of energy use and GHG emissions impacts could range from halving to doubling present day emissions, depending on consumer uptake and usage of the technology. As examples of positive impacts, the authors find that FAV deployment could reduce energy use if it leads to more eco-driving and platooning, and switching to smaller, less powerful cars, especially if deployed as part of shared mobility programs.

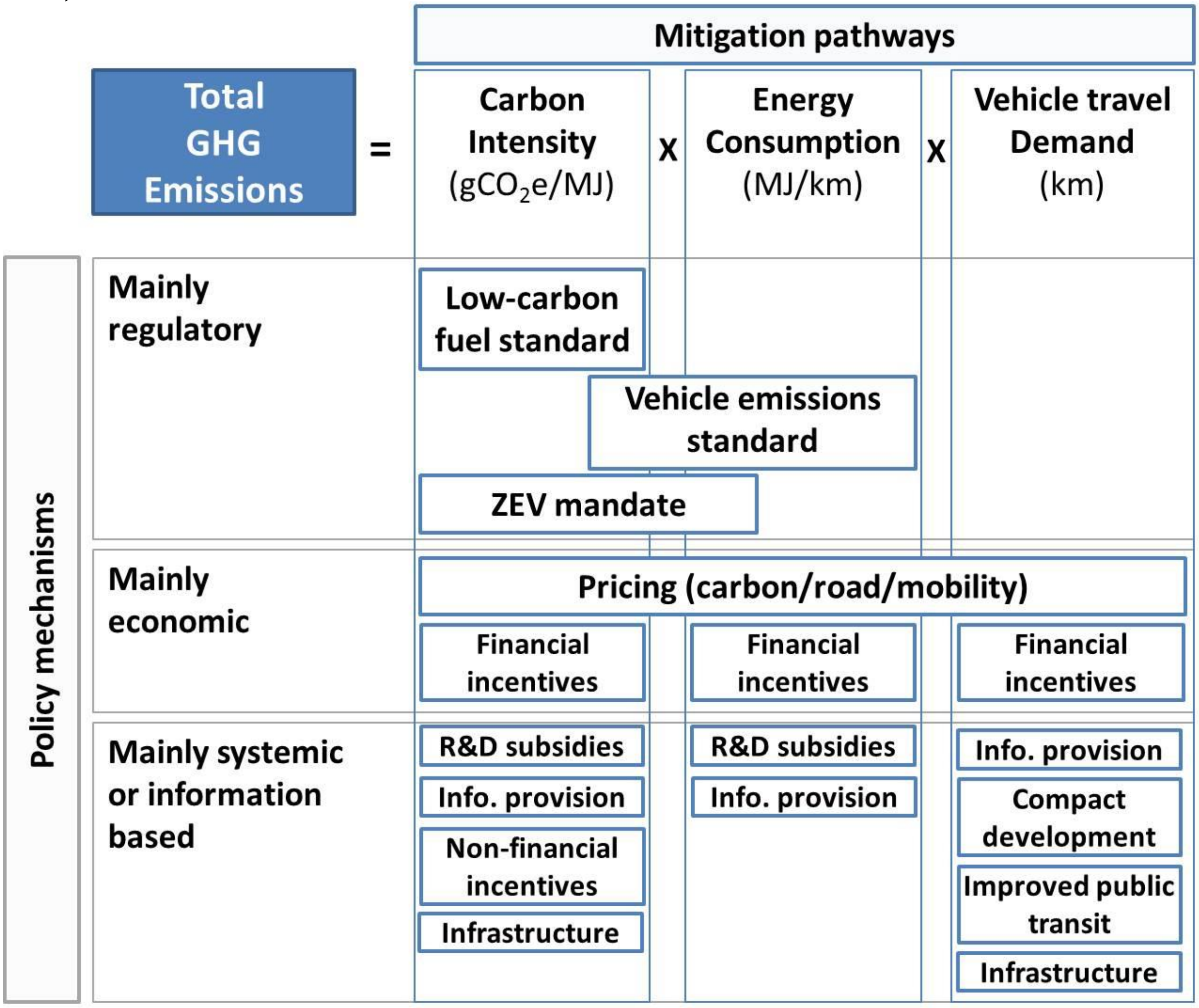
However, there are many potential negative impacts. FAVs could increase energy use if deployment leads to higher maximum highway speeds, increased vehicle driving due to new user groups such as elderly people and people with disabilities, and increased driving rates due to rebound effects from cheaper and easier travel (Wadud et al., 2016). Relatedly, Sperling et al. (2018a) describe the potential for an FAV "Hell" scenario where automation further entrenches private vehicle ownership over other modes and increases vehicle use. People with FAVs may be willing to drive more if it is cheaper per VKM, and if they can use travel time for other activities such as work. For example, FAVs could lower the costs of ride-hailing by removing the need for a driver. VKM may also increase due to "deadheading" or "empty" miles, when the FAV drives with no humans, say to park at home for free during the day while the owner is at a workplace, or for a ride-hailing program to find its next customer. Relatedly, decreasing driving and operation costs for freight trucks could similarly increase vehicle travel. One Sweden based simulation finds that FAVs could increase overall goods-movement or TKM by 22%, and increase trucking VKM by 35% (Engholm et al., 2021).

FAV technology brings many potential opportunities. To move towards the GHG-reducing scenarios, climate policy will likely have to play a strong role, especially road and carbon pricing. Others have proposed using tolls specifically to minimize zero-occupancy vehicle usage or dead-heading (Bahrami and Roorda, 2022). As noted, the optimal scenarios tend to occur when automation is combined with shared and electric mobility (Sperling et al., 2018b). A recent study finds that shared, electric FAVs could reduce GHG emissions by 20% compared to private owned electric FAVs—with 33% reductions if pooling is used (Vilaça et al., 2022). There also is a need for increased attention to urban planning, especially to avoid the potential for FAVs to increase demand for low-density, suburban-living that leads to longer commute distances (Milakis et al., 2017).

Climate Policy Options

This section provides a brief review of climate policies that can facilitate the effective deployment of deep decarbonization technologies. In particular, some of these policies can help assure that the low-carbon versions of the technologies are emphasized in technology innovation, development and usage. Below are brief summaries of most of the policies listed in Figure 2, which are depicted according to their focus on the three mitigation pathways noted in Section 2.1: switching to lower carbon fuels, improved energy efficiency, and reduced VKM.

Figure 2: Categorization of road transport policies by mitigation pathway (Source: Axsen et al., 2020)



While this section looks at several individual policy categories, evidence suggests that an integrative mix of strong policies is needed to induce a low-carbon transition. Such a mix likely requires a combination of pricing mechanisms, subsidies, regulations, and infrastructure implementation. Principles for effective policy mixes are described in more detail elsewhere (Axsen et al., 2020; Bhardwaj et al., 2020; Creutzig et al., 2011; Kivimaa and Kern, 2016; Sperling and Eggert, 2014). A comprehensive policy mix analysis ought to consider policy impacts and interactions according to numerous evaluation criteria, including GHG emission reductions, impacts to other societal co-benefits (air pollution, health, etc.), cost-effectiveness or efficiency, political or social acceptability, and transformative signal (Bhardwaj et al., 2020). Although these summaries are brief, next steps of this study can conduct more detailed policy evaluations regarding the deep decarbonization technologies in this report.

Most of the climate policy examples and research has focused on countries in Europe and North America, as well as China. While many findings can potentially transfer over to developing countries, it is clear that further research is needed to focus on their unique contexts.

8.1 Pricing mechanisms

Pricing is considered by many economists as the ideal climate policy mechanism due to potential effectiveness and efficiency. A carbon price is technology-neutral, allowing each rational consumer or firm to choose the lowest-cost mitigation option, be it low-carbon fuels, efficiency, or reduced travel, or simply to pay the tax and continue with the status quo (Azar and Sandén, 2011). Pricing can indeed play a strong role in deep GHG targets—if the price is high enough. The High-Level Commission on Carbon Prices indicates that Paris Agreement goals require carbon pricing in the range of US$40-80 per tonne of CO_2 by 2020, and US$50-100 per tonne of CO_2 by 2030 (High-Level Commission on Carbon Prices, 2017). Modeling suggests that a price-based mitigation strategy may need to reach well over these ranges by 2040 and 2050 (Bataille et al., 2018; Guivarch and

Rogelj, 2017). Pricing mechanisms currently exist in regions that account for only 20% of global GHG emissions, and fewer than 5% of those priced emissions are at levels consistent with Paris Agreement goals (World Bank Group, 2019).

Relatedly, road or mobility pricing can include carbon pricing and fuel taxes, but more often refers to cordon pricing,[45] congestion-based pricing, distance-based pricing, and parking prices. Although road pricing policies are often focused on congestion reduction or raising funds for transportation management, they can also cut CO_2 emissions by 2-13% (Cavallaro et al., 2018), and cut vehicle travel by 4-22% if implemented over decades (Rodier, 2009).

Across the different design types, road pricing schemes are most effective at CO_2 mitigation if based on travel or fuel consumption, rather than congestion reduction or other goals (Cavallaro et al., 2018; Rodier, 2009). Thinking more long-term, pricing can mitigate the anticipated rebound effects from cheap travel offered by future transport innovations, namely electrification, automation (Wadud et al., 2016), and ride-hailing (Coulombel et al., 2019). Others suggest that because ZEVs tend to be heavier than conventional ICE vehicles, future road or vehicle taxes should be partially based on vehicle weight (Galvin, 2022; Shaffer et al., 2021). However, a major challenge of pricing is public acceptability, as this approach evokes more public debate and opposition than other climate policies (Ardıç et al., 2018; Dreyer et al., 2015; Klenert et al., 2018; Rhodes et al., 2017).

8.2 Market-oriented regulations

A second broad category is market-oriented regulations, which provide clear and enforced requirements for fuels or vehicles. These regulations are "market-oriented" because they include market mechanisms such as credit-trading and competition among low-carbon technologies to improve policy cost-effectiveness.[46]

Three regulations in particular are increasing in popularity, while also showing promise for effectiveness in reducing GHG emissions (Axsen et al., 2020):

- Low-carbon fuel standard (LCFS): this policy focuses on reducing the carbon content of the fuels used to power transportation (gCO_2e/MJ). First implemented in California in 2007, versions are now in place in Canada and Europe. The policy assigns well-to-wheel emissions factors for each fuel type (including ethanol, biodiesel, electricity, and hydrogen) made from different feedstocks or sources. Typically, compliance credits are tradeable among fuel suppliers (including electric utilities) (Yeh et al., 2016).
- ZEV sales mandate: this policy targets automakers by requiring sales of a certain amount (or market share) of ZEVs. This approach was first implemented by California for light-duty vehicles, and versions are now in place in several other US states, two Canadian provinces and China. There are plans for heavy-duty versions in some jurisdictions as well. Most of these policies are now being updated to transition into an ICE ban, or 100% ZEV requirement, by 2035 or earlier. ZEV mandates have been shown to be effective in channeling innovation activities towards ZEV development (Sierzchula and Nemet, 2015; Wesseling et al., 2015), increasing the availability of ZEVs for sale (Bhardwaj et al., 2021; Slowik and Lutsey, 2018), and playing an important role in GHG mitigation targets (Sykes and Axsen, 2017).
- Vehicle emissions standard (VES): this policy sets a minimum performance requirement on fuel consumption and/or tail-pipe CO_2 emissions for newly sold vehicles (gCO_2e/km), which induces development of various technologies to improve efficiency, including ZEVs. Versions are in place in the EU, the US, Canada, Brazil, Japan, China, South Korea, Mexico and several other countries (Lipman, 2018).

At least in Canada and the US, all three market-oriented regulations tend to receive more citizen support than any pricing mechanism (Long et al., 2020; Long et al., 2021). Several modeling studies suggest that combining strong versions of these regulations can play an effective role in leading the way to achieve deep decarbonization goals for passenger and freight sectors (Axsen et al., 2020; Hammond et al., 2020; Lepitzki and Axsen, 2018; Sykes and Axsen, 2017).

8.3 Incentives

A third broad category is incentives, which include financial and non-financial forms. Most common are those that incentivize ZEV sales through purchase subsidies or exemptions from vehicle purchase taxes. There are also exemptions from road tolls, and access to high-occupancy vehicle lanes or bus lanes (Melton et al., 2017b). Generally speaking, such incentives tend to have high public acceptability (Melton et al., 2020; Rhodes et al., 2017). ZEV purchase subsidies can range from US$2500 to $20,000 per vehicle, where larger incentives can indeed boost ZEV sales (Axsen and Wolinetz, 2018; DeShazo et al., 2017; Hardman et al., 2017; Kurani et al., 2018; Wee et al., 2018).

[45] Cordon pricing is the application of a charge to drive into a particular area, say the downtown zone of a city.
[46] In contrast "pure" or "command-and-control" regulation would enforce the same technology requirement on every regulated agent, with no credit trading, and little or no choice among compliance options.

However, such incentives need to be in places for a long duration to have sustained GHG impacts (Hardman et al., 2017; Münzel et al., 2019), potentially for a decade or longer (Axsen and Wolinetz, 2018). Purchase incentives are generally found to be a less cost-effective policy, with the potential for inequitable outcomes (DeShazo et al., 2017). Though, such impacts can be improved through various design principles, such as putting caps on retail prices for eligible ZEVs, and caps on household incomes for those receiving the subsidy (DeShazo et al., 2017). "Non-financial" incentives, such as access to high-occupancy vehicle lanes for ZEVs (regardless of vehicle occupancy), are typically found to have a weak impact on long-term ZEV adoption (Hardman, 2019; Melton et al., 2020).

8.4 Deployment of charging and fueling infrastructure

The rollout of charging and refueling infrastructure can also support the adoption of ZEV sales, especially electric- and hydrogen-based infrastructure. Initiatives can include government sponsored charger and fueling stations, building standards that require charging infrastructure, or financial incentives for infrastructure installation. For light-duty PEVs, improvements to home charging opportunities typically has a higher impact than increased public or work-based charging (Hardman et al., 2018; Kormos et al., 2019; Melton et al., 2017a; Miele et al., 2020). That said, increased public charging is identified as an important goal, especially to support adoption among car-buyers that live in attached homes and apartments (IEA, 2021c). As noted above, charging infrastructure faces more challenging barriers for heavy-duty vehicles, which may require more advanced technology such as Mega-chargers or catenary systems. Increased hydrogen fueling infrastructure is particularly necessary for FCEV deployment (light- and heavy-duty), though it is not necessarily a sufficient condition for widespread sales (IEA, 2021d; Miele et al., 2020).

8.5 Research and development subsidies

Finally, subsidies for research & development (R&D) can support technology advancements in any of the deep decarbonization technologies noted above, including improvements in advanced batteries (cost and performance), fuel-cell technology, mega-chargers, catenaries, advanced biofuels, forms of shared mobility, and automation technology. Lessons from the past suggest that R&D support for alternative fuels is not successful if it is in place for only a few years at a time, especially if funding is repeatedly moved from one low-carbon fuel option to another (Melton et al., 2016). Rather, sustained support is needed to overcome the many transformative barriers that are faced by new deep decarbonization technologies (Weber and Rohracher, 2012).

That said, many of the policies noted above can also send a strong, long-term transformative signal to private industry to channel innovation activity into ZEVs and other low-carbon technology. The signal can occur as long as the policy or policy mix is suitably stringent and long-term, with clear enforcement and penalties for non-compliance, and trust that the policy will stay in place over time (Bhardwaj et al., 2021; Sierzchula and Nemet, 2015).

Summary

Of the deep decarbonization technologies reviewed here, the highest readiness is observed for light-duty and bus PEVs (TRL 10-11), both of which also hold strong potential for substantially decreasing GHG emissions. Readiness is lower for FCEVs (TRL 8), which remain expensive for light-duty and heavy-duty applications, with very limited refueling infrastructure, as well as many remaining barriers to assure that most hydrogen produced to be "green". Readiness for advanced biofuels is also low (TRL 7-9). They have a potential advantage given that they can be used in blends with existing gasoline or diesel-based engines, but the development and market penetration of low-carbon ethanol and biodiesel has been limited in the last decade.

In terms of shifting travelers away from private vehicle ownership, several forms of shared mobility have made dramatic market progress in the last year, namely ride-hailing, car-sharing and micro-mobility. However, these modes have not substantially displaced privately owned vehicles, nor is there clear evidence of a net carbon benefit.

Finally, vehicle automation is in a relatively early state of development (TRL 4+), and the potential future impacts are enormously uncertain. Such technology would likely need to be carefully paired with low-carbon fuels and/or shared mobility, as well as strong climate policy, to achieve the more optimistic automation scenarios.

This preliminary analysis is focused on the technology readiness of the case technologies, as well as market progress and potential for GHG reductions. It is beyond the scope of this first report to provide specific recommendations. However, it is clear that the observed technology readiness and GHG potential is highest for PEVs, with more challenges and limited potential for FCEVs and advanced biofuels. Several shared mobility options have demonstrated high market readiness, but so far limited potential for GHG reduction. The noted climate policies can help to support further development of each technology, and to assure that R&D and innovation activity is directed towards low-carbon versions of each.

9.1 Next steps

The next steps of this paper could include several additions. First is more comprehensive analysis of the social, institutional, economic and business barriers and opportunities for each technology. Second is to uncover additional detail on the barriers and opportunities for developing countries, including countries in Africa, Southeast Asia, and Central & South America. Third is to further evaluate the noted climate policy categories, particularly their ability to overcome these identified barriers.

Based on feedback, next steps may also add several deep decarbonization technology categories to this list. These may include:

- Smart charging technologies, such as vehicle-to-grid (V2G), vehicle-to-home (V2H) and time-of-use programs.
- Specific battery chemistries, notably lithium-ion and solid-state batteries.
- Other battery issues, such as materials, recycling and second-life or second-use of batteries.
- Electrified road systems, such as overhead catenary lines for heavy-duty vehicles.
- Advanced chargers, such as mega-chargers for heavy-duty PEVs.

References

Acheampong, R.A., Siiba, A., 2020. Modelling the determinants of car-sharing adoption intentions among young adults: the role of attitude, perceived benefits, travel expectations and socio-demographic factors. Transportation 47, 2557-2580.

Alonso-Mora, J., Samaranayake, S., Wallar, A., Frazzoli, E., Rus, D., 2017. On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment. Proceedings of the National Academy of Sciences 114, 462.

Ambrose, H., Kendall, A., Lozano, M., Wachche, S., Fulton, L., 2020. Trends in life cycle greenhouse gas emissions of future light duty electric vehicles. Transportation Research Part D: Transport and Environment 81, 102287.

Ardıç, Ö., Annema, J.A., Molin, E., van Wee, B., 2018. The association between news and attitudes towards a Dutch road pricing proposal. Transportation 45, 827-848.

Arias-Molinares, D., García-Palomares, J.C., 2020. The Ws of MaaS: Understanding mobility as a service fromaliterature review. IATSS Research 44, 253-263.

Axsen, J., Plötz, P., Wolinetz, M., 2020. Crafting strong, integrated policy mixes for deep CO2 mitigation in road transport. Nature Climate Change 10, 809-818.

Axsen, J., Wolinetz, M., 2018. Reaching 30% plug-in vehicle sales by 2030: Modeling incentive and sales mandate strategies in Canada. Transportation Research Part D: Transport and Environment 65, 596-617.

Ayetor, G.K., Opoku, R., Sekyere, C.K.K., Agyei-Agyeman, A., Deyegbe, G.R., 2021. The cost of a transition to electric vehicles in Africa: A case study of Ghana. Case Studies on Transport Policy.

Azar, C., Sandén, B.A., 2011. The elusive quest for technology-neutral policies. Environmental Innovation and Societal Transitions 1, 135-139.

Bahrami, S., Roorda, M., 2022. Autonomous vehicle parking policies: A case study of the City of Toronto. Transportation Research Part A: Policy and Practice 155, 283-296.

Baptista, P., Melo, S., Rolim, C., 2014. Energy, Environmental and Mobility Impacts of Car-sharing Systems. Empirical Results from Lisbon, Portugal. Procedia - Social and Behavioral Sciences 111, 28-37.

Bataille, C., Guivarch, C., Hallegatte, S., Rogelj, J., Waisman, H., 2018. Carbon prices across countries. Nature Climate Change 8, 648-650.

Bataille, C., Li, F., 2021. Emerging climate technologies in the energy supply sector. Technology Executive Committee, UNFCCC.

Bento, A.M., Klotz, R., Landry, J.R., 2015. Are there Carbon Savings from U.S. Biofuel Policies? The Critical Importance of Accounting for Leakage in Land and Fuel Markets. The Energy Journal 36, 75-109.

Bhardwaj, C., Axsen, J., Kern, F., McCollum, D., 2020. Why have multiple climate policies for light-duty vehicles? Policy mix rationales, interactions and research gaps. Transportation Research Part A: Policy and Practice 135, 309-326.

Bhardwaj, C., Axsen, J., McCollum, D., 2021. Simulating automakers' response to zero emissions vehicle regulation. Transportation Research Part D: Transport and Environment 94, 102789.

BloombergNEF, 2021. Battery Pack Prices Fall to an Average of $132/kWh, But Rising Commodity Prices Start to Bite. Bloomberg.

Booto, G.K., Aamodt Espegren, K., Hancke, R., 2021. Comparative life cycle assessment of heavy-duty drivetrains: A Norwegian study case. Transportation Research Part D: Transport and Environment 95, 102836.

Brand, C., Götschi, T., Dons, E., Gerike, R., Anaya-Boig, E., Avila-Palencia, I., de Nazelle, A., Gascon, M., Gaupp-Berghausen, M., Iacorossi, F., Kahlmeier, S., Int Panis, L., Racioppi, F., Rojas-Rueda, D., Standaert, A., Stigell, E., Sulikova, S., Wegener, S., Nieuwenhuijsen, M.J., 2021. The climate change mitigation impacts of active travel: Evidence from a longitudinal panel study in seven European cities. Global Environmental Change 67, 102224.

Bucher, D., Buffat, R., Froemelt, A., Raubal, M., 2019. Energy and greenhouse gas emission reduction potentials resulting from different commuter electric bicycle adoption scenarios in Switzerland. Renewable and Sustainable Energy Reviews 114, 109298.

California Air Resources Board, 2020. Low Carbon Fuel Standard Reporting Tool Quarterly Summaries.

Cavallaro, F., Giaretta, F., Nocera, S., 2018. The potential of road pricing schemes to reduce carbon emissions. Transport Policy 67, 85-92.

Cervero, R., Golub, A., Nee, B., 2007. City CarShare: Longer-Term Travel Demand and Car Ownership Impacts. Transportation Research Record: Journal of the Transportation Research Board 1992, 70-80.

Chen, J., Wang, F., He, X., Liang, X., Huang, J., Zhang, S., Wu, Y., 2022. Emission mitigation potential from coordinated charging schemes for future private electric vehicles. Applied Energy 308, 118385.

Clewlow, R.R., Mishra, G.S., 2017. Disruptive Transportation: The Adoption, Utilization, and Impacts of Ride-Hailing in the United States, UCD-ITS-RR-17-07. UC Davis, Davis, California.

Coulombel, N., Boutueil, V., Liu, L., Viguie, V., Yin, B., 2019. Urban ridesharing's substantial rebound effects: Simulating travel decisions in Paris, France. Transportation Research Part D: Transport and Environment.

Creutzig, F., McGlynn, E., Minx, J., Edenhofer, O., 2011. Climate policies for road transport revisited (I): Evaluation of the current framework. Energy Policy 39, 2396-2406.

Cullen, D.A., Neyerlin, K.C., Ahluwalia, R.K., Mukundan, R., More, K.L., Borup, R.L., Weber, A.Z., Myers, D.J., Kusoglu, A., 2021. New roads and challenges for fuel cells in heavy-duty transportation. Nature Energy 6, 462-474.

DeShazo, J.R., Sheldon, T.L., Carson, R.T., 2017. Designing policy incentives for cleaner technologies: Lessons from California's plug-in electric vehicle rebate program. Journal of Environmental Economics and Management 84, 18-43.

Dreyer, S.J., Walker, I., McCoy, S.K., Teisl, M.F., 2015. Australians' views on carbon pricing before and after the 2013 federal election. Nature Climate Change 5, 1064.

Eisenmeier, S.R., 2018. Ride-sharing platforms in developing countries: effects and implications in Mexico City Pathways for Prosperity Commission. Background Paper Series; no. 3. Oxford. United Kingdom.

Engholm, A., Kristoffersson, I., Pernestal, A., 2021. Impacts of large-scale driverless truck adoption on the freight transport system. Transportation Research Part A: Policy and Practice 154, 227-254.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M., 2006. Ethanol Can Contribute to Energy and Environmental Goals. Science 311, 506-508.

Figenbaum, E., 2017. Perspectives on Norway’s supercharged electric vehicle policy. Environmental Innovation and Societal Transitions 25, 14-34.

Firnkorn, J., Müller, M., 2011. What will be the environmental effects of new free-floating car-sharing systems? The case of car2go in Ulm. Ecological Economics 70, 1519-1528.

Galvin, R., 2022. Are electric vehicles getting too big and heavy? Modelling future vehicle journeying demand on a decarbonized US electricity grid. Energy Policy 161, 112746.

GOV.UK, 2021. COP26 declaration on accelerating the transition to 100% zero emission cars and vans.

Greenblatt, J.B., Saxena, S., 2015. Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. Nature Climate Change 5, 860.

Guivarch, C., Rogelj, J., 2017. Carbon Price Variations in 2°C scenarios explored. Carbon Price Leadership Coalition.

Hall, D., Nicholas, M., Bernard, M.R., 2021. Working paper: Guide to electrifying ride-hailing vehicles for cities. International Council for Clean Transportation.

Hammond, W., Axsen, J., Kjeang, E., 2020. How to slash greenhouse gas emissions in the freight sector: Policy insights from a technology-adoption model of Canada. Energy Policy 137, 111093.

Hardman, S., 2019. Understanding the impact of reoccurring and non-financial incentives on plug-in electric vehicle adoption – A review. Transportation Research Part A: Policy and Practice 119, 1-14.

Hardman, S., Chandan, A., Tal, G., Turrentine, T., 2017. The effectiveness of financial purchase incentives for battery electric vehicles – A review of the evidence. Renewable and Sustainable Energy Reviews 80, 1100-1111.

Hardman, S., Jenn, A., Tal, G., Axsen, J., Beard, G., Daina, N., Figenbaum, E., Jakobsson, N., Jochem, P., Kinnear, N., Plötz, P., Pontes, J., Refa, N., Sprei, F., Turrentine, T., Witkamp, B., 2018. A review of consumer preferences of and interactions with electric vehicle charging infrastructure. Transportation Research Part D: Transport and Environment 62, 508-523.

Hasselwander, M., Bigotte, J.F., Antunes, A.P., Sigua, R.G., 2022. Towards sustainable transport in developing countries: Preliminary findings on the demand for mobility-as-a-service (MaaS) in Metro Manila. Transportation Research Part A: Policy and Practice 155, 501-518.

Hensher, D.A., Ho, C.Q., Reck, D.J., 2021. Mobility as a service and private car use: Evidence from the Sydney MaaS trial. Transportation Research Part A: Policy and Practice 145, 17-33.

High-Level Commission on Carbon Prices, 2017. Report of the High-Level Commission on Carbon Prices.

Hoekstra, A., 2019. The Underestimated Potential of Battery Electric Vehicles to Reduce Emissions. Joule 3, 1412-1414.

Hosford, K., Fuller, D., Lear, S.A., Teschke, K., Gauvin, L., Brauer, M., Winters, M., 2018. Evaluation of the impact of a public bicycle share program on population bicycling in Vancouver, BC. Preventive Medicine Reports 12, 176-181.

ICCT, 2018. Automation in the long haul: Challenges and opportunities of autonomous heavy duty trucking in the United States. ICCT.

ICCT, 2021a. Decarbonizing road transport by 2050: Accelerating the global transition to zero-emission vehicles. ICCT.

ICCT, 2021b. A Global Comparison of the Life-cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars. ICCT.

IEA, 2019. Innovation Gaps. IEA, Paris, France.

IEA, 2020a. Advanced Biofuels -- Potential for Cost Reduction. IEA, Paris, France.

IEA, 2020b. Tracking Transport 2020. IEA, Paris, France.

IEA, 2021a. Electric vehicles. IEA, Paris, France.

IEA, 2021b. ETP Clean Energy Technology Guide. International Energy Agency (IEA), Paris, France.

IEA, 2021c. Global EV Outlook 2021: Accelerating ambitions despite the pandemic. International Energy Agency, Paris, France.

IEA, 2021d. Global Hydrogen Review 2021. IEA, Paris, France.

IEA, 2021e. Net Zero by 2050. IEA, Paris, France.

IEA, 2021f. Transport Biofuels. IEA, Paris, France.

IEA, 2021g. Trucks and Buses. IEA, Paris, France.

International Energy Agency, 2019. Tracking Transport. IEA, Paris, France.

IRENA, 2019. Innovation Outlook: Smart Charging for Electric Vehicles. International Renewable Energy Agency, Abu Dhabi.

Jochem, P., Frankenhauser, D., Ewald, L., Ensslen, A., Fromm, H., 2020. Does free-floating carsharing reduce private vehicle ownership? The case of SHARE NOW in European cities. Transportation Research Part A: Policy and Practice 141, 373-395.

Kacperski, C., Ulloa, R., Klingert, S., Kirpes, B., Kutzner, F., 2022. Impact of incentives for greener battery electric vehicle charging – A field experiment. Energy Policy 161, 112752.

Kamiya, G., Axsen, J., Crawford, C., 2019. Modeling the GHG emissions intensity of plug-in electric vehicles using short-term and long-term perspectives. Transportation Research Part D: Transport and Environment 69, 209-223.

Karkour, S., Rachid, S., Maaoui, M., Lin, C.-C., Itsubo, N., 2021. Status of life cycle assessment (LCA) in Africa. Environments 8.

Kent, J.L., Dowling, R., 2013. Puncturing automobility? Carsharing practices. Journal of Transport Geography 32, 86-92.

Kivimaa, P., Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Research Policy 45, 205-217.

Klenert, D., Mattauch, L., Combet, E., Edenhofer, O., Hepburn, C., Rafaty, R., Stern, N., 2018. Making carbon pricing work for citizens. Nature Climate Change 8, 669-677.

Kormos, C., Axsen, J., Long, Z., Goldberg, S., 2019. Latent demand for zero-emissions vehicles in Canada (Part 2): Insights from a stated choice experiment. Transportation Research Part D: Transport and Environment 67, 685-702.

Kumar, S., Shrestha, P., Abdul Salam, P., 2013. A review of biofuel policies in the major biofuel producing countries of ASEAN: Production, targets, policy drivers and impacts. Renewable and Sustainable Energy Reviews 26, 822-836.

Kurani, K.S., Caperello, N., TyreeHageman, J., Davies, J., 2018. Symbolism, signs, and accounts of electric vehicles in California. Energy Research & Social Science 46, 345-355.

Labee, P., Rasouli, S., Liao, F., 2022. The implications of Mobility as a Service for urban emissions. Transportation Research Part D: Transport and Environment 102, 103128.

Lajevardi, M.S., Axsen, J., Crawford, C., 2019. Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement costs: Simulations of freight routes in British Columbia. Transportation Research Part D: Transport and Environment 76, 19-55.

Lempert, R., Zhao, J., Dowlatabadi, H., 2019. Convenience, savings, or lifestyle? Distinct motivations and travel patterns of one-way and two-way carsharing members in Vancouver, Canada. Transportation Research Part D: Transport and Environment 71, 141-152.

Lemphers, N., Bernstein, S., Hoffmann, M., Wolfe, D.A., 2022. Rooted in place: Regional innovation, assets, and the politics of electric vehicle leadership in California, Norway, and Québec. Energy Research & Social Science 87, 102462.

Lepitzki, J., Axsen, J., 2018. The role of a low carbon fuel standard in achieving long-term GHG reduction targets. Energy Policy 119, 423-440.

Li, Y., Taghizadeh-Hesary, F., 2022. The economic feasibility of green hydrogen and fuel cell electric vehicles for road transport in China. Energy Policy 160, 112703.

Liimatainen, H., van Vliet, O., Aplyn, D., 2019. The potential of electric trucks – An international commodity-level analysis. Applied Energy 236, 804-814.

Lipman, T.E., 2018. Emerging Technologies for Higher Fuel Economy Automobile Standards. Annual Review of Environment and Resources 42, 267-288.

Long, Z., Axsen, J., Kitt, S., 2020. Public support for supply-focused transport policies: Vehicle emissions, low-carbon fuels, and ZEV sales standards in Canada and California. Transportation Research Part A: Policy and Practice 141, 98-115.

Long, Z., Kitt, S., Axsen, J., 2021. Who supports which low-carbon transport policies? Characterizing heterogeneity among Canadian citizens. Energy Policy 155, 112302.

Martin, E., Shaheen, S.A., Lidicker, J., 2010. Impact of Carsharing on Household Vehicle Holdings: Results from North American Shared-Use Vehicle Survey. Transportation Research Record 2143, 150-158.

Matyas, M., Kamargianni, M., 2018. The potential of mobility as a service bundles as a mobility management tool. Transportation.

Melton, N., Axsen, J., Goldberg, S., 2017a. Evaluating plug-in electric vehicle policies in the context of long-term greenhouse gas reduction goals: Comparing 10 Canadian provinces using the “PEV policy report card”. Energy Policy 107, 381-393.

Melton, N., Axsen, J., Goldberg, S., Moawad, B., Wolinetz, M., 2017b. Canada's ZEV Policy Handbook. Sustainable Transportation Action Research Team (START), Simon Fraser University,, Vancouver, Canada.

Melton, N., Axsen, J., Moawad, B., 2020. Which plug-in electric vehicle policies are best? A multi-criteria evaluation framework applied to Canada. Energy Research & Social Science 64, 101411.

Melton, N., Axsen, J., Sperling, D., 2016. Moving beyond alternative fuel hype to decarbonize transportation. Nature Energy 1, 1-10.

Miele, A., Axsen, J., Wolinetz, M., Maine, E., Long, Z., 2020. The role of charging and refuelling infrastructure in supporting zero-emission vehicle sales. Transportation Research Part D: Transport and Environment 81, 102275.

Milakis, D., van Arem, B., van Wee, B., 2017. Policy and society related implications of automated driving: A review of literature and directions for future research. Journal of Intelligent Transportation Systems 21, 324-348.

Moultak, M., Lutsey, N., Hall, D., 2017. Transitioning to zero-emission heavy-duty freight vehicles. The International Council on Clean Transportation (ICCT) San Francisco, USA.

Münzel, C., Plötz, P., Sprei, F., Gnann, T., 2019. How large is the effect of financial incentives on electric vehicle sales? – A global review and European analysis. Energy Economics, 104493.
Rajper, Z.S., Albrecht, J., 2020. Prospects of Electric Vehicles in the Developing Countries: A Literature Review. Sustainability 12.
Reck, D.J., Martin, H., Axhausen, K.W., 2022. Mode choice, substitution patterns and environmental impacts of shared and personal micro-mobility. Transportation Research Part D: Transport and Environment 102, 103134.
Rhodes, E., Axsen, J., Jaccard, M., 2017. Exploring Citizen Support for Different Types of Climate Policy. Ecological Economics 137, 56-69.
Rodier, C., 2009. Review of International Modeling Literature: Transit, Land Use, and Auto Pricing Strategies to Reduce Vehicle Miles Traveled and Greenhouse Gas Emissions. Transportation Research Record 2132, 1-12.
Rodier, C., 2018. The Effects of Ride Hailing Services on Travel and Associated Greenhouse Gas Emissions. Institute of Transportation Studies, UC Davis, Davis, USA.
Rogers, E., 2003. Diffusion of Innovations (5th Ed.). Free Press, New York.
Schaller, B., 2017. Unsustainable? The Growth of App-Based Ride Services and Traffic, Travel and the Future of New York City. Schaller Consulting.
Schwerdfeger, S., Bock, S., Boysen, N., Briskorn, D., 2021. Optimizing the electrification of roads with charge-while-drive technology. European Journal of Operational Research.
Sen, B., Ercan, T., Tatari, O., 2017. Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. Journal of Cleaner Production 141, 110-121.
Shaffer, f.B., Auffhammer, M., Samaras, C., 2021. Make electric vehicles lighter to maximize climate and safety benefits. Nature 598, 254-256.
Shah, S.A.H., Hisashi, K., 2021. Analyzing travelers' attitude towards ride-hailing services in developing countries: Case of Lahore, Pakistan. IATSS Research.
Shaheen, S., 2018. Shared Mobility: The Potential of Ridehailing and Pooling, in: Sperling, D. (Ed.), Three Revolutions: Steering Automated, Shared and Electric Vehicles to a Better Future. Island Press, Washington DC.
Shaheen, S.A., Cohen, A., 2020. Innovative Mobility: Carsharing Outlook; Carsharing Market Overview, Analysis, and Trends (Spring 2020), University of California, Berkeley.
Shi, K., Shao, R., De Vos, J., Cheng, L., Witlox, F., 2021. The influence of ride-hailing on travel frequency and mode choice. Transportation Research Part D: Transport and Environment 101, 103125.
Sierzchula, W., Nemet, G., 2015. Using patents and prototypes for preliminary evaluation of technology-forcing policies: Lessons from California's Zero Emission Vehicle regulations. Technological Forecasting and Social Change 100, 213-224.
Slowik, S., Lutsey, N., 2018. The Continued Transition to Electric Vehicles in U.S. Cities. The International Council on Clean Transportation (ICCT), San Francisco, USA.
Sopjani, L., Stier, J.J., Ritzén, S., Hesselgren, M., Georén, P., 2019. Involving users and user roles in the transition to sustainable mobility systems: The case of light electric vehicle sharing in Sweden. Transportation Research Part D: Transport and Environment 71, 207-221.
Sovacool, B.K., Daniels, C., AbdulRafiu, A., 2022. Transitioning to electrified, automated and shared mobility in an African context: A comparative review of Johannesburg, Kigali, Lagos and Nairobi. Journal of Transport Geography 98, 103256.
Sperling, D., 2018. Three Revolutions: Steering automated, shared, and electric vehicles to a better future. Island Press, Washington, DC.
Sperling, D., Eggert, A., 2014. California's climate and energy policy for transportation. Energy Strategy Reviews 5, 88-94.
Sperling, D., Pike, S., Chase, R., 2018a. Will the Transportation Revolutions Improve Our Lives--or Make Them Worse?, in: Sperling, D. (Ed.), Three Revolutions: Steering automated, shared, and electric vehicles to a better future. . Island Press, Washington, DC.
Sperling, D., van der Meer, E., Pike, S., 2018b. Vehicle Automation: Our Best Shot at a Transportation Do-Over?, in: Sperling, D. (Ed.), Three Revolutions: Steering automated, shared, and electric vehicles to a better future. Island Press, Washington, DC.
Subramaniam, Y., Masron, T.A., 2021. The impact of economic globalization on biofuel in developing countries. Energy Conversion and Management: X 10, 100064.
Sykes, M., Axsen, J., 2017. No free ride to zero-emissions: Simulating a region's need to implement its own zero-emissions vehicle (ZEV) mandate to achieve 2050 GHG targets. Energy Policy 110, 447-460.
Viegas, J., Martinez, L.M., Crist, P., 2016. Shared Mobility: Innovation for Liveable Cities. OECD International Transport Forum Corporate Partnership Board, Paris, France.
Vilaça, M., Santos, G., Oliveira, M.S.A., Coelho, M.C., Correia, G.H.A., 2022. Life cycle assessment of shared and private use of automated and electric vehicles on interurban mobility. Applied Energy 310, 118589.
Wadud, Z., MacKenzie, D., Leiby, P., 2016. Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transportation Research Part A: Policy and Practice 86, 1-18.

Wang, K., Liu, H., Cheng, L., Bian, Z., Circella, G., 2022. Assessing the role of shared mobility services in reducing travel-related greenhouse gases (GHGs) emissions: Focusing on America's young adults. Travel Behaviour and Society 26, 301-311.

Wang, Y., Shi, W., Chen, Z., 2021. Impact of ride-hailing usage on vehicle ownership in the United States. Transportation Research Part D: Transport and Environment 101, 103085.

Weber, K.M., Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. Research Policy 41, 1037-1047.

Wee, S., Coffman, M., La Croix, S., 2018. Do electric vehicle incentives matter? Evidence from the 50 U.S. states. Research Policy 47, 1601-1610.

Wesseling, J.H., Farla, J.C.M., Hekkert, M.P., 2015. Exploring car manufacturers' responses to technology-forcing regulation: The case of California's ZEV mandate. Environmental Innovation and Societal Transitions 16, 87-105.

Whiston, M.M., Lima Azevedo, I.M., Litster, S., Samaras, C., Whitefoot, K.S., Whitacre, J.F., 2022. Expert elicitation on paths to advance fuel cell electric vehicles. Energy Policy 160, 112671.

Wolinetz, M., Axsen, J., Peters, J., Crawford, C., 2018. Simulating the value of electric-vehicle–grid integration using a behaviourally realistic model. Nature Energy 3, 132-139.

World Bank Group, 2019. State and Trends of Carbon Pricing 2019. World Bank Group, Washington, DC, USA.

Yan, X., Yang, W., Zhang, X., Xu, Y., Bejleri, I., Zhao, X., 2021. A spatiotemporal analysis of e-scooters' relationships with transit and station-based bikeshare. Transportation Research Part D: Transport and Environment 101, 103088.

Yang, H., Huo, J., Bao, Y., Li, X., Yang, L., Cherry, C.R., 2021. Impact of e-scooter sharing on bike sharing in Chicago. Transportation Research Part A: Policy and Practice 154, 23-36.

Yeh, S., Witcover, J., Lade, G.E., Sperling, D., 2016. A review of low carbon fuel policies: Principles, program status and future directions. Energy Policy 97, 220-234.

Yin, J., Qian, L., Shen, J., 2019. From value co-creation to value co-destruction? The case of dockless bike sharing in China. Transportation Research Part D: Transport and Environment 71, 169-185.

Ziedan, A., Shah, N.R., Wen, Y., Brakewood, C., Cherry, C.R., Cole, J., 2021. Complement or compete? The effects of shared electric scooters on bus ridership. Transportation Research Part D: Transport and Environment 101, 103098.