United Nations Climate Change
Technology Executive Committee

DEEP DECARBONIZATION TECHNOLOGIES FOR SUSTAINABLE ROAD MOBILITY


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FOREWORD

To achieve the goals of the Paris Agreement, countries are required to peak greenhouse gas emissions as soon as possible and achieve climate neutrality by mid-century. It is of paramount importance to make efforts to transform and decarbonize energy systems in order to align with the Paris goals.

Transport sector has a critical role to play in achieving the Paris Agreement and Sustainable Development Goals. In their nationally determined contribution documents, most Parties indicate 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.

Road transport is one of the world's biggest carbon emission challenges and its emission continuously growing. The deep decarbonization of the energy sector including transport could greatly contribute to meeting the emission target. 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 offer comprehensive solutions to reduce emission.

It is in this context that the Technology Executive Committee worked to identify challenges and opportunities to strengthen enabling environments to enhance replicability and scalability of technologies for sustainable transport.

The technical paper looks at selected technologies and solutions for sustainable road mobility and:

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 opportunities related to their development and effective deployment;

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

We believe that this paper provides policymakers and other relevant stakeholders with a set of information and analysis to help their decision- making when defining national and regional strategies for accelerating the scale-up and diffusion of these technologies.

We would like to express our heartfelt appreciation to the members of the enabling environment and capacity-building task force of Technology Executive Committee and representatives of observer organizations who have provided their valuable contributions to this paper.

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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 CO_2 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. Key barriers to deployment and adoption remain, including relatively high purchase prices, limited charging opportunities, impacts to the grid, impacts from batteries, limited availability, and limited consumer awareness and preferences. However, there are many opportunities to address these barriers through various stakeholder efforts, especially policies such as a ZEV sales mandate, low-carbon fuel standard, charger deployment, and purchase incentives. Heavy-duty PEVs face some stronger technological barriers, notably the added challenges of charging infrastructure.

Readiness is lower for FCEVs (TRL 8), which has more extreme versions of the barriers noted for PEVs, such as very high purchase costs for light-duty and heavy-duty applications, very limited refueling infrastructure, limited vehicle availability, and limited consumer demand. The production of "green" or "blue" hydrogen needs to be substantially improved and expanded for this technology to play a role in deep decarbonization scenarios. Various opportunities and policies can help with FCEV deployment and commercialization, though PEVs seem likely to outcompete FCEVs in most road transport applications, except perhaps for long-haul heavy-duty vehicles.

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 2021	Carbon impacts (well-to-wheel or lifecycle)	Role in IEA NZE 2050 Scenario
Plug-in electric vehicle (PEV)[a]	Light-duty	10-11	1-15% new market share in many countries; 86% 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 (~40k 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 (~5k buses, 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 2021. 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.

Readiness for advanced biofuels is also relatively low (TRL 7-9). It has proven a challenge to develop and deploy low-carbon ethanol and biodiesel, while also avoiding negative impacts to food prices and food security. There is a potential advantage given that biofuels can be used in blends with existing gasoline or diesel-based engines, especially "drop-in" fuels that require no engine modification. However, 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 few years, notably ride-hailing, car-sharing, and micro-mobility. However, the biggest barrier to the realization of the low-carbon versions of these modes is that there is no clear evidence of a net carbon benefit, nor of substantially displacing ownership of private vehicles. Further, it is unclear if the availability of these modes can shift consumer preference away from private vehicle ownership.

Finally, vehicle automation is in a relatively early stage 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. Key barriers to the development of low-carbon versions of automation include consumer confusion and lack of interest regarding the technology, and continued consumer preference for private rather than shared versions of automation.

This report also evaluates 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 (R&D). Evidence is summarized for each regarding effectiveness in reducing GHG emissions, cost-effectiveness or efficiency, equity impacts, political acceptability, and transformative signal. The report also considers the ability of each policy type to address the barriers noted above.

Evidence indicates that a coherent policy mix is most likely to be successful in addressing multiple policy evaluation criteria and barriers to technology uptake. Market-oriented regulations such as low-carbon fuel standards, vehicle emissions standards, and ZEV sales mandates can provide a balance of effectiveness and political acceptability, while sending a clear transformative signal to industry and stakeholders. Other policies can play supportive roles in an effective policy mix. While pricing can be the most cost-effective policy, it tends to suffer from high political opposition at the high stringency needed to be effective. Purchase incentives can boost ZEV sales but are costly to governments in the long-run. Deployment of charging infrastructure and fueling infrastructure can also support strong regulations in achieving 100% ZEV sales goals. Important knowledge gaps remain as to how to best implement an effective policy mix in developing countries.

ACRONYMS

ASEAN	Association of Southeast Asian Nations
BEV	battery-electric vehicles
BECCS	bioenergy with carbon capture and storage
CARB	California Air Resources Board
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
H2	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
LCFS	low-carbon fuel standard
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
TOU	time-of-use
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
VES	vehicle emissions standard
VKM	vehicle-kilometers travelled
WTW	well-to-wheels

1. INTRODUCTION

The Paris Agreement clearly states the importance of GHG mitigation goals to achieve 1.5°C and 2.0°C warming targets. 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; Melton et al., 2016). 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 to achieve the 1.5°C warming target. 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 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 travel 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 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

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.

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. Summarize key barriers and opportunities relating to social, institutional, economic, and business aspects of their development and effective deployment; and

3. Identify and evaluate innovative policy options, opportunities, and challenges for policymakers to effectively support the deployment of these technologies.

Section 9 summarizes key messages and potential actions for policymakers and other stakeholders, as well as identifying priority items that could be expanded in future research efforts.

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

2. 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 trucks, 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 ZEVs, low-carbon fuels, and 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.

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/.

2.2 Methodological approach

A literature review was conducted to achieve the objectives stated in Section 1, with 228 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.

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.

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/.

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 complete 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 defined as 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, including advanced batteries.

This report summarizes available evidence on WTW and LCA impacts. 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]

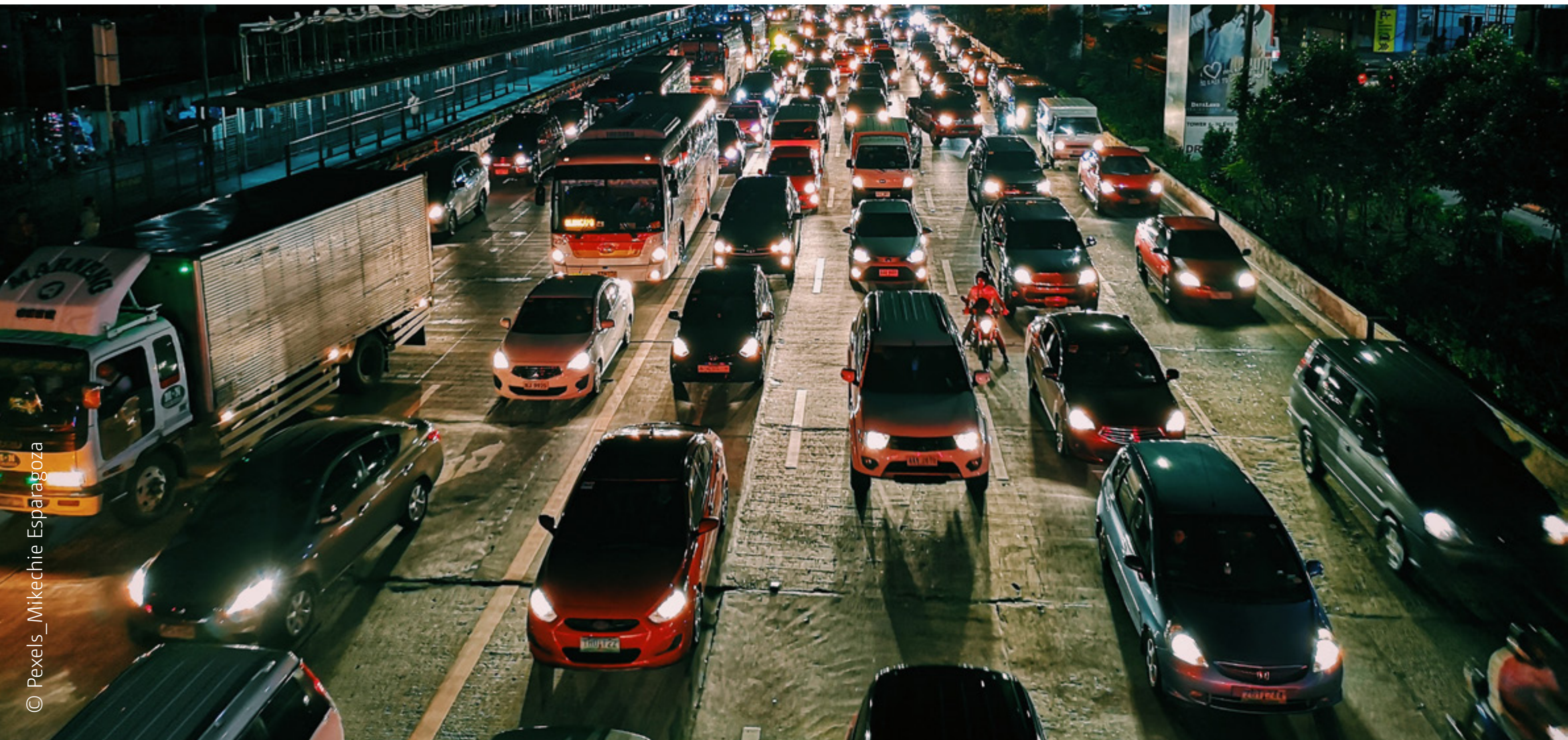
Finally, this report considers opportunities and barriers relating to social, institutional, economic, and business conditions for each broad technology category. This analysis considers more than just the state of technology, GHG emissions, and financial costs—but also the broader context that can prevent or support market success. Considerations include:

- Consumer, user, and market acceptance of the technology, including awareness, perceptions, and preferences for particular technology attributes (often compared to the conventional, incumbent technology being replaced).

- Broader public or acceptance or opposition to the technology, which may relate to cultural preferences, or concerns about safety or risk.

- Institutional conditions, such as the regulatory environment, existence of supportive (or oppositional) organizations, and capacity and knowledge to sustain a transition.

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



3. 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 considers 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 Europe, China, and North America, 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 internal combustion engine (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).

Across the world, there were about 450 different PEV car models available for sale in 2021, which is a 15% increase from 2020 (IEA, 2022). 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 reached 1.8 million in 2021, with almost 500,000 being installed in that year (IEA, 2022).

14 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 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.

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About one-third of these were fast chargers (IEA, 2022). The total numbers of public chargers in 2021 is highest in the China, followed by Europe, then the US (IEA, 2022). 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).

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). In 2021, PEV market share grew to nearly 10% of new light-duty vehicle sales, pushing stock to over 16 million (IEA, 2022).

Sales rates vary widely across countries. The 2021 leaders were Norway (86% of new market share being PEVs), Iceland (72%), Sweden (43%%), the Netherlands (30%), Germany (26%), France (19%), the UK (19%), Italy (9%), and Spain (8%) (IEA, 2022). Comparing larger markets, Europe leads with 17% new market share in 2021, followed by China (16%) and the US (5%) (IEA, 2022). Only a small fraction of PEV sales and stock are outside these three regions, and some regions have seen market stagnation. In 2020 for example, PEV sales declined in Japan and New Zealand.

Most developing countries have negligible PEV sales; for example, PEV sales are lower than 0.5% in Brazil, Indonesia, and India (IEA, 2022). As some positive news, 2021 saw substantial sales increases in Asia, Latin America and the Caribbean, and Asia, which aligned with increases in PEV model availability in those regions (IEA, 2022). Further, countries such as 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 countries in 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. That said, the actual energy savings will highly depend on how the vehicles are used (Karanam et al., 2022).

18 https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/2021_event04/304526331cac4d7786df7eca18c315/a9510c1bd7244c5783fa8caa46ce3fce.pdf.

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, ICCT 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 (also found by Hsieh et al., 2022)
- **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).

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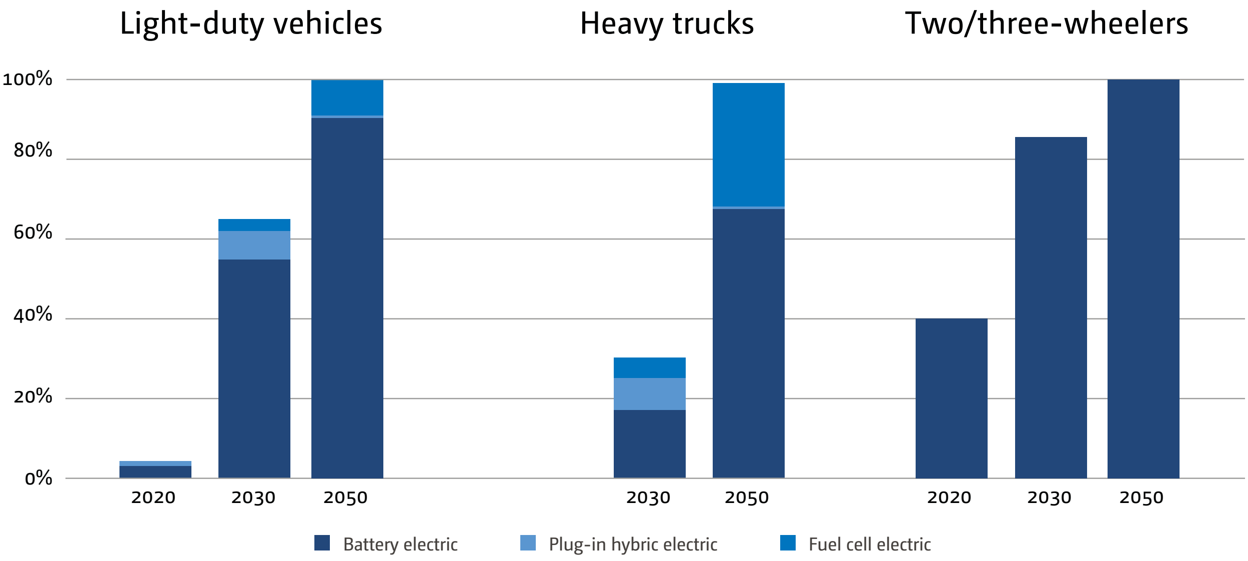
Figure 1 IEA Net Zero Emissions Scenario assumptions on penetration of battery electric, plug-in hybrid and fuel-cell electric vehicles



Source: IEA, 2021e.

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). 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 global 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 PEV models is 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 technological 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). There are additional catenary trials in France and the Netherlands (IEA, 2022).

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.
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.

3.2.2 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). The 2021 global stock was about 670,000 electric buses (IEA, 2022). 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 bus sales are negligible in most developing countries, though India is planning to purchase 5,500 electric buses (IEA, 2022).

- **Heavy-duty trucks**: The global heavy-duty PEV truck market reached sales of 7,400 in 2020 (a 10% increase from 2019), and the global stock is about 66,000 (IEA, 2022). 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). Heavy-duty 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 four 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).

- Singapore: a lifecycle-based study of BEV delivery trucks found that using the 2019 electricity grid mix could reduce GHG emissions by 11% (Yeow et al., 2022).

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.

3.3 Barriers for plug-in electric vehicles

Table 3 summarizes the major social, institutional, economic, and business barriers that PEVs face globally. First is the higher price of PEVs relative to conventional vehicles. While battery costs have substantially declined, BEVs still require a price premium, especially for larger vehicles and heavy-duty applications. Consumer research suggests that only a minority segment of car buyers are willing to pay such a premium for light-duty PEVs (Kormos et al., 2019). High prices tend to be even more of barrier for developing countries with lower household income (IEA, 2022). For example, consumer research in India suggests that potential PEV buyers became less interested in purchase once they learned about the costs of purchasing and owning a PEV (Munshi et al., 2022).

Table 3 Barriers and opportunities for plug-in electric vehicles

	Barrier	Opportunities	Policies (Section 8)
1	High costs (especially developing countries)	Lower cost PEVs, two/three-wheeler opportunities	Purchase subsidies, low-interest loans, ZEV mandate
2	Limited charging	Public-private partnerships, fast charging, battery swapping, catenary lines (heavy-duty)	Charger deployment; subsides for home, work, and public charger installation; regulation for easier installation
3	Grid impacts	Coordinate PEV deployment with renewable development, smart charging, smaller PEVs (two/three-wheeler)	Time-of-use (TOU) pricing
4	Battery source materials	Expand domestic materials mining and manufacturing; increased R&D for other battery chemistries (e.g., cobalt-free)	Regulation for mining and extraction, requirements for use of recycled material
5	Consumer awareness and preferences	Better marketing, demonstration, setting norms, link PEVs to renewables	ZEV mandate, information campaigns
6	Model availability/variety	Support newer PEV automakers; expand domestic auto industry	ZEV mandate
7	Fleet/commercial challenges	Better marketing, demonstration, increased model availability/variety	ZEV mandate, purchase subsidies, information campaigns for fleets
8	Equity impacts	Policy design for equity goals	Careful design of taxes and subsides (e.g., discounts for lower-income households)

Second is limitations in charging infrastructure. Research shows that in regions with large proportions of single-family dwellings and private garages have ample opportunities for home charging, especially in North America (Axsen and Kurani, 2012b; Miele et al., 2020). However, limited charging infrastructure is as an important barrier in most of the world (IEA, 2022), including India (Murugan and Marisamynathan, 2022) and Spain (Rosales-Tristancho et al., 2022). Additional (and faster) charging can support PEV mobility, while also sending social signals to normalize the usage of PEVs (White et al., 2022), and increase consumer trust that further charging infrastructure will be provided over time (Munshi et al., 2022). That said, deployment of public charging infrastructure continues to need government support due to a typically weak business case or lack of profit (Kim et al., 2022). The business case is likely to remain similarly weak for installation of the more powerful chargers needed for heavy-duty vehicles, in the 350 kW to 1 MW range (IEA, 2022).

Third is the impact of widespread PEV usage on regional electricity grids. Increasing market share of PEVs inevitably leads to increasing electricity demand, which can require changes in electrical infrastructure to support increasing generation capacity, and distribution to particular areas with more PEVs being charged. Research suggests that in many regions, existing grid capacity will be effective to support PEV demand up to 2030, but may require serious adaptations past that point, especially as PEV stock reaches 20% and beyond (IEA, 2022). For some developing countries, a sizeable proportion of citizens have limited access to electricity, such as only about 40% of citizens in Zimbabwe, and 60% of those in Vanuatu (Rawat et al., 2021). Further, in some countries, existing capacity is often already strained (Rawat et al., 2021). Deployment of PEVs and chargers will need to be carefully coordinated with other electricity needs.

Fourth is the availability of battery materials, notably lithium, cobalt, and nickel—each of which faced higher prices in May 2022 compared to early 2021, a trend that is highly linked to Russia's war with Ukraine (IEA, 2022). These metals are mostly extracted by a few companies, in countries such as Australia, Chile, and the Democratic Republic of Congo, while battery production is concentrated in China (IEA, 2022). Analysis suggest that known metal sources would be sufficient to meet PEV sales growth until the end of the 2020s, but supply will need to increase to meet 2030 sales goals and beyond (IEA, 2022). Others argue that shortages in cobalt in particular are inevitable, where more effort is needed to develop cobalt-free batteries (Zeng et al., 2022). Improvements in technology for advanced battery recycling can further help with supply shortages. Some regions such as the EU are proposing standards to require a certain percentage of battery material to come from recycling sources (Hoarau and Lorang, 2022).

The remaining barriers relate more directly to consumer and social issues. Fifth is limitations in consumer awareness and preferences regarding PEVs. Research continues to show that many consumers have low awareness and understanding of PEVs (Long et al., 2019a), where PEV awareness is associated with PEV interest in several countries (Murugan and Marisamynathan, 2022; Rosales-Tristancho et al., 2022; Sahoo et al., 2022). Research in all many regions shows that PEV interest is linked to motives to improve the environment (Kormos et al., 2019; Munshi et al., 2022; Rosales-Tristancho et al., 2022), making PEVs a more difficult sell to consumers that do not have strong environmental values. There also remain important concerns about the reliability and safety of PEVs (Murugan and Marisamynathan, 2022), and lack of trust in the technology (Sahoo et al., 2022). Somewhat relatedly, social norms can also play important roles in PEV adoption, where consumers are more likely to purchase a vehicle if they see others buying PEVs, or come to believe that society thinks they should purchase a PEV (Nayum and Thøgersen, 2022).

Sixth, PEV model availability is an important barrier, as has been found in North America (Matthews et al., 2017), Europe (Zarazua de Rubens et al., 2018), and India (Murugan and Marisamynathan, 2022). As noted in Section 3.1.1, PEV model availability has been steadily increasing. However, availability and variety in a given region tends to be much more limited than that offered for conventional vehicles. Research shows that it is important to have a wide range of easily available PEVs, as consumer needs in any country are quite diverse (Ferguson et al., 2018; Murugan and Marisamynathan, 2022). Further, even if a given model is offered for sale in a region, PEVs often are not available for test drives due to lack of inventory, and purchase may require waiting lists of weeks or months.

Seventh are challenges specific to fleet and commercial vehicle buyers, which purchase light-duty PEVs at about one-quarter the global rate for passenger PEVs (IEA, 2022). Challenges to this segment include a wider diversity of vehicle usage patterns, weaker regulations for efficiency and ZEVs, and fewer suitable PEV model options (IEA, 2022). Research with UK fleets finds that the biggest barriers to PEV purchase are cost of ownership and operation suitability (Skippon and Chappell, 2019). As with passenger PEVs, commercial PEVs are more attractive to organizations and users with higher environmental concern (Roemer and Henseler, 2022).

A final barrier involves concerns of social inequity relating to PEV uptake, most notably in the pattern that PEV supportive policies may benefit only higher-income households (Caulfield et al., 2022; Sovacool et al., 2019). In particular, devoting public tax dollars to PEVs rather than public transit tends to provide less benefit to lower-income households (Eliasson and Mattsson, 2006). Such equity concerns may also reduce the public acceptability of PEV-supportive policies (noted further in Section 8).

3.4 Opportunities for plug-in electric vehicles

To overcome these important barriers, there are numerous social, institutional, economic, and business opportunities to help support PEV market development. First and foremost is the importance of PEV-supportive policy, noted in the right-hand column of Table 3, and further explored in Section 8. 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. 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 put more emphasis on lower-cost PEVs to develop markets for lower-income households and users, and also to make PEVs more accessible to developing countries (Sovacool et al., 2022). Clearly, the use of purchase subsidies can directly lower the cost of PEVs, and programs can be designed to focus on lower-income households (see Section 8). In some cases, total cost of ownership might already be lower for BEVs, for example with one analysis of Ghana finding a 30% cost reduction compared to conventional vehicles (Ayetor et al., 2021). PEVs can also offer a benefit to islands of Pacific and African regions, such as Nauru, Vanuatu, and STP, where oil imports face a high price and put ICEs at a disadvantage (Rawat et al., 2021).

Although not a focus of this report, two- and three-wheelers present an opportunity for low-cost electrification, along with lesser grid impacts due to smaller batteries (IEA, 2021c). Many of the urban areas of countries in South Asia and Africa already depend on two/three-wheelers (Rawat et al., 2021). A study of Cambodia finds that electric motorcycles tend to have lower total costs of ownership than gasoline motorcycles (Rawat et al., 2021), while research on four cities in Africa (Johannesburg, Kigali, Lagos and Nairobi) also finds market potential for low cost e-bikes and e-scooters (Sovacool et al., 2022). Similar cost savings are seen for electric three-wheelers in Pakistan, while leading to a net reduction in GHG emissions (Khan et al., 2022). Similarly, electrifying motorcycle taxis in Kampala, Uganda can yield substantial reductions in GHG emissions and local air pollutants (Vanatta et al., 2022). For these reasons, several

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developing countries have announced financial subsidies or other support for electric two- and three-wheelers, including India (the largest two-wheeler market in the world), China, Thailand, and Indonesia (IEA, 2022). Of course, 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.

A third opportunity is to improve charging for light-duty vehicles. While charging infrastructure continues to grow substantially each year, substantially more is needed to meet ambitious PEV sales targets (IEA, 2022). Analysis of EU data suggests deployment of fast charging in particular can play a strong role in supporting further PEV adoption (Rostad Sæther, 2022). Some regions are still exploring the potential for “battery-swapping” stations to provide rapid recharging of BEVs, which is found to have consumer support in China (Tan et al., 2022). More generally, the installation of home charging can be facilitated by changing building codes to either require charger installation, or at least to make it easier for consumers to install home chargers. Offering financial incentives for home and public charger installation can also improve the business case. Finally, improved stakeholder coordination, notably private-public partnerships, will help to structure charger deployment globally, including developing countries such as India (Sahoo et al., 2022). Other developing countries will surely benefit from such partnerships to find affordable solutions for charger expansion (Rawat et al., 2021).

Fourth is improving charging infrastructure for the particularly challenging case of heavy-duty vehicles (noted in Section 3.2.1). While some heavy-duty PEVs can be charged nightly at a depot, others will need higher power charging such as Megachargers, on road-based chargers such as catenaries, or perhaps some version of the battery-swapping stations noted above. Further R&D is needed to improve technical feasibility, as well as stakeholder consultation. As one example, modeling research in Germany suggests that a network of 267 fast chargers (with 2 to 8 chargepoints per location), could meet the needs of 15% heavy-duty BEV truck stock (Speth et al., 2022). Comparable research in the US indicates that a network of 450 kW charging units at California’s rest areas could similarly support heavy-duty BEVs for long-haul usage (Burke, 2022).

Fifth, 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). One approach to smart charging is to utilize time-of-use (TOU) or real time pricing for PEV charging, where higher prices are charged either when electricity demand is high, or more carbon-intensive sources of electricity need to be utilized (such as natural gas “peaker” plants). Analyses demonstrate that TOU pricing can effectively shift PEV charging behaviour, though it is only likely to reduce GHG emissions if real time pricing is linked to carbon intensity (Li and Jenn, 2022). Some studies suggest that consumers are more interested in PEV purchase if their usage can be linked to renewable sources of energy, as has been found in research in Korea (Moon et al., 2022), and the US (Axsen and Kurani, 2013). PEV deployment can also be linked to opportunities to expand solar in some African countries, notably Ghana and Nigeria (Rawat et al., 2021).

Sixth is developing sustainable mining opportunities of battery materials. For example, Zimbabwe has large lithium deposits that could be developed (Rawat et al., 2021), which could boost domestic battery and PEV availability. Of course, extraction processes need to be low-carbon, while also being conducted in ways that maintaining labour rights and support local economies. More effort is also needed to improve battery recycling, such as the joint ventures among battery manufacturer's seeking a "battery recycling hub" in Norway, with similar efforts underway in China, Korea, and the UK (Rawat et al., 2021).

Seventh is building consumer awareness and positive experience with PEVs. Modeling shows that increasing awareness alone can substantially increase PEV demand (Wolinetz and Axsen, 2017), and that increasing consumer experience with new vehicle technology can increase positive preferences (Axsen et al., 2009). When consumers lack experience with new vehicle technology, they can rely strongly on learning from others in their social network (Axsen and Kurani, 2011, 2012a; Kurani et al., 2018). In particular, social interactions help consumers to learn to learn of the existence and basic function of PEVs, such as electric driving range and performance (Chakraborty et al., 2022), as well as help develop the symbolic values of PEVs and how they might connect to their personal identity (Long and Axsen, 2022). It is possible that information campaigns as well as PEV demonstrations and trials can help to further develop the PEV market, though little is known about how to best design such outreach strategies. Strong regulations such as a ZEV mandate can also induce automakers to more effectively market PEVs to broader audiences. Effective stakeholder coalitions can also help to normalize the PEV transition, which could build consumer confidence in the new technology (Lemphers et al., 2022).

Eighth is to increase PEV model availability and variety, where consumer interest in PEVs is increased when there are more PEVs available for sale, in a wider variety of makes, models, and vehicle classes (Bhardwaj et al., 2021; Wolinetz and Axsen, 2017). One particularly strong method of increasing PEV availability is through a ZEV regulation, notably a ZEV sales mandate. With such a mandate, automakers are incentivized to develop more ZEV models in more classes over time. Automakers will be induced to supply and market these vehicles in regions where the policy is in place (Bhardwaj et al., 2021). U.S.-based analyses indicate that regions under the jurisdiction of the ZEV mandate have had relatively higher ZEV availability (Lutsey et al., 2015; Slowik and Lutsey, 2018). Forward-looking modeling studies of Canada show that increased ZEV supply is needed to achieve ambitious ZEV sales goals for 2030 and beyond (Axsen and Wolinetz, 2018; Bhardwaj et al., 2021; Miele et al., 2020; Wolinetz and Axsen, 2017). National ZEV regulation could also help to develop a domestic PEV auto industry in some developing countries, to help move away from the present patterns that rely on importing used vehicles from other countries (Rawat et al., 2021). Such regulations could also be used to improve trends with used vehicles, in particular to make sure that developed countries are not "dumping" less efficient or higher carbon used vehicles into developing country markets.[25]

Another opportunity is to better support PEV adoption among fleets and commercial operators. Whether using light-duty or heavy-duty vehicles, these users tend to focus on financial costs for purchase and operation, and in some cases also environmental impact or identity (Cantillo et al., 2022). These segments can be better supported through targeted financial incentives, as well as extending existing efficiency and ZEV regulations to apply to commercial applications. Targeted information campaigns may be helpful as well, notably for smaller firms that have less resources to investigate new PEV technology.

Finally, the noted equity impacts can be improved through careful policy design. For example, PEV purchase incentives can result in more equitable outcomes if designed to only be eligible for lower cost PEVs, and available to lower-income households (DeShazo et al., 2017).

25 https://news.un.org/en/story/2020/10/1076202.

4. 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 included the Honda Clarity, Toyota Mirai, and Hyundai Nexo, which have driving ranges around 500-700km and take several minutes to refuel.[26] 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.[27]

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 (IEA, 2021c), and about 730 in 2021 (IEA, 2022). 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 globally by 2030 and 90,000 by 2050.

Another potential barrier is that FCEVs are inherently less efficient than PEVs from a thermodynamic perspective, especially for green hydrogen, due to the need to convert electricity to hydrogen and back to electricity again.

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). The total FCEV stock increased by a further 50% from 2020 to 2021 (IEA, 2022)

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

4.1.3 Carbon impacts

As noted, the GHG emissions impacts vary strongly with the source of hydrogen. Clearly, hydrogen produced from renewable electricity and forest residue biomass tends to have the lowest lifecycle emissions, while there is also a carbon reduction from using landfill gas (ICCT, 2021c). However, lifecycle impacts are more uncertain for hydrogen produced from natural gas and coal, even with carbon capture and storage, and other sources such as manure and wastewater sludge. Depending on method, impacts from these sources range from a slight emissions increase, to a substantial decline (ICCT, 2021c). Even blue hydrogen, produced from natural gas with CCS, can have high emissions when accounting for fugitive methane emissions (Howarth and Jacobson, 2021).

Generally, the use of hydrogen in FCEVs can yield net GHG 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). Of course, the net GHG impacts of vehicles will depend on various assumptions, such as driving distances, and inclusion of hydrogen leakage.

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 on 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 730 hydrogen fueling stations globally in 2022.

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 in 2021 had about 90% of the FCEV buses and 95% of the FCEV trucks globally (IEA, 2022) .

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. Consider studies from four different countries:

- **Canada**: 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).
- **Norway**: a lifecycle-based study finds that heavy-duty FCEVs can cut GHG emissions by 48% when including GHG impacts from vehicle and drivetrain manufacturing (Booto et al., 2021).
- **China**: a WTW-based study indicates that green-hydrogen powered FCEVs heavy trucks and buses can reduce WTW emissions by 60-77% (Li and Taghizadeh-Hesary, 2022).
- **Singapore**: a lifecycle-based study of FCEV delivery trucks found that using grey hydrogen could reduce GHG emissions by 23-30% (Yeow et al., 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).

As noted, FCEVs may prove to be more competitive than BEVs for heavy-duty applications that have a longer daily range, such as exceeding 450km per day (IEA, 2021e). Simulations of competition among heavy-duty ZEVs finds that FCEVs gain more market share for long-haul trucks travelling more than 332 km daily, relative to short-haul trucks (Lajevardi et al., 2022). Though competition between BEVs and FCEVs will surely also depend on whether hydrogen refueling infrastructure or electric charging infrastructure deployment is prioritized in a given region (Lajevardi et al., 2022).

4.3 Barriers for fuel cell electric vehicles

FCEVs face several important barriers to deployment and adoption (Table 4), including the clear technology limitations: high purchase price, high cost fuel, and very limited fueling infrastructure (IEA, 2022). As already noted above, the high costs of fuel cells and high price for hydrogen leads to relatively high costs of ownership that typically exceed those of PEVs in most contexts (IEA, 2022). Further, hydrogen refueling infrastructure is highly limited, which reduces the feasibility and functionality of FCEVs in most regions. Also, there is also presently limited capacity to produce lower-carbon forms of hydrogen, notably "green" and "blue" sources. Put together, this makes the FCEV technology quite limited in terms of GHG mitigation potential, economic costs, and business case. These high costs make a transition to FCEVs an even more difficult prospect for developing countries.

Table 4 Barriers and opportunities for fuel-cell electric vehicles

	Barrier	Opportunities	Policies (Section 8)
1	High price	International alliances, R&D to bring down costs, focus on heavy-duty applications	Purchase subsidies, hydrogen fuel subsidies, ZEV mandate
2	Very limited refueling	Public-private partnerships, R&D activity, and subsidies	Subsidies for refueling installations, ZEV mandate
3	Limited green hydrogen generation	Expand renewable capacity, R&D activity, and subsidies	Subsidies, low-carbon fuel standards
4	Consumer awareness and preferences	Improved marketing and demonstration	ZEV mandate, information campaigns, purchase incentives
5	Model availability/variety	Support FCEV automakers; expand FCEV industry	ZEV mandate
6	Competition from BEVs	Focus on long-haul heavy-duty applications	Match PEV policies for FCEVs

Not surprisingly, these high costs and limited infrastructure translate into barriers to consumer demand. Consumer research in Spain suggest that high purchase price and low fuel availability are the main barriers to consumer interest (Rosales-Tristancho et al., 2022). A study of Korean consumers finds there that FCEVs are the least desirable ZEV, especially if fueled by "grey" hydrogen (Moon et al., 2022). Canadian research similarly finds that BEVs or PHEVs are more desirable to mainstream consumers than FCEVs (Kormos et al., 2019; Long et al., 2019b). Interestingly, the few consumers that prefer FCEVs tend to have lower environmental values than BEV intenders (Long et al., 2019b). Further, FCEVs have even lower model availability than PEVs in most regions (IEA, 2022), often with zero models or only one model available for sale, which presents an enormous barrier to consumer uptake.

Put in another light, it could be said that the biggest barrier to widespread FCEV uptake is competition from other ZEVs, namely BEVs and PHEVs. Presently, PEVs are cheaper to purchase and operate and can make use of much more widespread electricity infrastructure. There are also far more models available for sale, especially for light-duty vehicles. Further development of advanced batteries and fast-charging technology might only widen the gap between BEVs and FCEVs (Plötz, 2022). For these reasons, many scenarios of deep decarbonization assume that PEVs will dominate over FCEVs in most transport sectors, except perhaps for long-haul heavy-duty applications (IEA, 2021e).

4.4 Opportunities for fuel cell electric vehicles

There are numerous opportunities for FCEVs—mainly in the realms of innovation and policy. Of course, 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.

One major opportunity is increased investment in and support for innovation activity by the private and public sector. The IEA identifies government R&D spending on hydrogen as a “priority action” for achieving net zero goals, potentially increasing investment in enabling infrastructure to 40 times today’s investment level by 2030 (IEA, 2021e). In particular, the IEA identifies hydrogen electrolyzers as a substantial innovation opportunity, one of three that may be essential to achieve the NZE scenario, along with advanced batteries and direct air capture and storage (IEA, 2021e). Development of hydrogen technology clearly needs more R&D activity, demonstration projects, and systems to move and transport hydrogen. With increased innovation activity, 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).

Relatedly, further FCEV development will require further capacity building, especially the continued activity of international alliances to help with sharing hydrogen-related 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). Research in the Philippines puts emphasis on the need to support and expand partnerships between industry and academia to develop both FCEV and hydrogen technology, reaching a critical mass of experts and R&D activity (Abeleda Jr and Espiritu, 2022)

Until vehicle and fuel costs substantially decline, continued is surely required to sustain FCEV sales. The limited success of 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 R&D breakthroughs to drastically increase production levels and bring down manufacturing costs.

Further, FCEVs will also benefit from ZEV-supportive policies that include similar incentives for FCEVs as are already available for BEVs. This includes the noted purchase subsidies 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 and blue hydrogen. As explained further in Section 8, these regulations include ZEV sales mandates and low-carbon fuel standards. Vehicle regulations such as a ZEV mandate can also help to increase FCEV model availability.

To focus on innovation activity with the higher potential for success, it seems important for FCEV development to focus on what is widely perceived to be its most viable transport application: heavy-duty vehicles with long-haul usage patterns (IEA, 2021e). This could be an area where FCEVs out-compete BEVs in terms of function and lifecycle costs, providing a niche where further technology learning could occur to bring down costs and improve performance.

5. 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.[28] 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 on pure biofuel (unblended). "Drop-in" 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 a major distinction is made 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).

28 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.

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),[29] which addresses GHG goals but not necessarily other sustainability goals. In the NZE scenario, biofuels produced with CCS are 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.[30] 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),

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

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 in Section 5.1. 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).

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.[31] 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 produced 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 impacts 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.

31 https://en.wikipedia.org/wiki/Flexible-fuel_vehicle.

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%.[32]

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.[33] Advanced forms of biodiesel made up 16% of the global biodiesel mix in 2020 (IEA, 2021f). 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 chemical composition that is the nearly identical to diesel and thus allows up to 100% blends with no engine modifications. HDRD production has developed in Singapore for export to countries such as the US and Canada.[34]

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%.[35]

32 https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/04-03_MENDES_SOUZA.pdf.
33 https://www.nrcan.gc.ca/energy-efficiency/transportation-alternative-fuels/alternative-fuels/biofuels/biodiesel/3509.
34 https://afdc.energy.gov/fuels/emerging_hydrocarbon.html.
35 https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/04-03_MENDES_SOUZA.pdf.

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 assumed to increase by over 3.5 times from 2020 to 2030 in the NZE. 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 with ambitious climate policies in place, including a low-carbon fuel standard (Lepitzki and Axsen, 2018).

5.4 Barriers for advanced biofuels

The largest barriers to the development and deployment of advanced ethanol and biodiesel relate to the defining characteristics of "advanced biofuels", namely requiring the avoidance of food crop competition, and requiring significant lifecycle reductions in GHG emissions (Table 5).

Table 5 Barriers and opportunities for advanced biofuels

	Barrier	Opportunities	Policies (Section 8)
1	Impacts to food prices and security	Focus on crops that don't compete with food (notably developing countries), develop partnerships (public, academic, industry) to plan land use	Include food/land considerations in LCFS policy
2	High carbon sources	Invest in "advanced" biofuels, invest in CCS	LCFS, link subsidies to low carbon content
3	High price	R&D in advanced feedstocks (e.g., switchgrass, wheat straw, HDRD), develop low-cost resources in developing countries	Subsidies, LCFS
4	Limited refueling	Public-private partnerships	Refueling deployment, LCFS
5	Lack of compatible vehicle stock	Develop "drop-in" fuels (e.g., HDRD)	ZEV mandate, information campaigns

Regarding food, it is inevitable that expanded biofuel demand and production will have some impact on global commodity prices in agriculture as well as food security for a given region (Koizumi, 2015). For example, increasing bioethanol demand in the US leads to higher corn prices, which leads to more croplands being allocated to corn, and less to competing crops such as soybeans. Increasing corn prices also increases the price of livestock feed and thus livestock, and can then also impact global prices for feed grains and soybeans (Koizumi, 2015). Increasing food prices can also have a negative impact on food security (Koizumi, 2015). However, the magnitude of food impacts can vary strongly by feedstock and region. For example, one study finds that ethanol production competes with maize used for food in Mexico and thus reduces food security, while biodiesel production in Indonesia does not substantially compete with food (Boly and Sanou, 2022). Similarly, sugarcane production in Brazil has been able to expand by increasing the use of arable land, rather than reducing production of other crops (Koizumi, 2015). Other research suggests that negative impacts to food security may only be short term, where long term, sustained investment in biofuel production could lead to a stabilization of food prices, and perhaps even improve food security (Subramaniam et al., 2020).

A second barrier is the potential for conventional biofuels to lead to minimal reductions in GHG emissions from a lifecycle perspective, and perhaps even an increase in emissions. For example, Section 5.2.2 notes the potential increase in emissions from ethanol produced from wheat or barley/rye in Europe. Clearly, the selection of biofuel feedstocks and production methods must be aligned with the deep decarbonization goals.

Further, advanced biofuels face many of the same challenges as PEVs and FCEVs regarding high costs, limited refueling infrastructure, and limited availability of vehicle compatible with higher biofuel blends. Advanced biofuels in particular can be two to three times more costly than fossil fuels, and in general are also more costly than conventional biofuels (IEA, 2020a). As with PEVs and FCEVs, biofuel deployment requires the expansion of refueling infrastructure—though this is not likely to be as costly as for hydrogen. Similarly, changes are needed in light- and heavy-duty vehicles to allow higher blends, unless “drop-in” fuels such as HDRD prove to be successful.

5.5 Opportunities for advanced biofuels

As with hydrogen, there are numerous opportunities to support innovation in advanced, low-carbon biofuels. For goals of food security, development needs to focus on "advanced" biofuel feedstocks and processes, and away from conventional crops that tend to compete with foods, notably sugarcane, corn, and soybeans (IEA, 2021e). As noted, there is particular potential for development of advanced biofuels in developing countries, where in some cases expansion in the long-run might not come at the expense of cropland and may not induce higher food prices (Boly and Sanou, 2022; Koizumi, 2015). However, it is quite difficult to research and anticipate the impacts of biofuel development on food prices. Development will require careful planning, and increases in institutional capacity, ideally with sharing across nations, and partnerships that include input from government, industry, and academia.

Another major opportunity for biofuel development is for policymakers to send a clear signal for research and development to focus on low-carbon forms of ethanol and biodiesel. There is substantial potential to develop lower-cost production methods for advanced biofuels such as cellulosic ethanol, HDRD, and biofuel with CCS (or BECCS). Policies in developed and developing countries alike could be designed to support further development of low-carbon biofuels in developing countries, notably Latin America and Africa, provided that various sustainability goals are also achieved.[36]

Some 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 LCFS, 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). Further, 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 to design policies 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).

Further, there is potential for efforts to further reduce the production costs of advanced biofuels. Increasing R&D activity and technology experience could reduce production costs by 5-27% compared to today, and with largescale deployment costs could be cut a further 50% in the most optimistic cases (IEA, 2020a). Research shows that ethanol blending mandates have helped to increase R&D effort and innovation (Nelson et al., 2022), and in the future could expand the use of cellulosic ethanol from agricultural residues (Schuenemann and Delzeit, 2022).

36 https://www.ieabioenergyconference2021.org/wp-content/uploads/2021/12/04-03_MENDES_SOUZA.pdf.

6. 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, 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 falls from 35% to 20%, and the proportion of two-car households falls from 13% to 5% (IEA, 2021e).

This section summarizes several existing and emerging forms of shared mobility and their potential roles in deep decarbonization: ride-hailing, car-sharing, micro-mobility, 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 to increase overall vehicle occupancy (Sperling, 2018).

The costs of different shared mobility modes can vary widely by type, country, and context. In the US for example, in ride-hailing trips in dollars per VKM can cost considerably more than VKM traveled in a new or used vehicle (Sperling, 2018). Though, a pooled ride-hailing trip can be 30-40% cheaper per VKM than using ride-hailing as alone. Of course, private vehicle ownership and usage has many other differences from shared mobility that explain the different levels of uptake, such as consumer perceptions of convenience, comfort, and privacy.

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 in most countries (Shaheen, 2018). Uber is now available in more than 10,000 cities in 71 countries worldwide.[37] 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, and it is increasing in China with higher reported usage than in the US.[38] 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 isolate and quantify 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), as also found in simulation modeling of Rio de Janeiro, Brazil (Silva et al., 2022). Other studies find potential for ride-hailing to complement public transit and active travel, and to reduce VKM, at least for some consumer groups in China (Gao et al., 2022), and the US (Lee et al., 2022). A study in Haikou, China finds that pooled ride-hailing can reduce VKM by 8% compared to standard ride-hailing (Zhu and Mo, 2022).

While net impacts are uncertain, it is suggested that ride-hailing is leading to a slight increase in GHG emissions in some regions, including 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., 2022b). However, heavier weekday usage may increase GHG emissions (Wang et al., 2022b). 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., 2019a). 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).[39] 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).

37 https://www.uber.com/global/en/cities/.
38 https://www.weforum.org/agenda/2017/05/hailing-a-ride-china-leads-the-way-on-mobility-apps/.
39 Car-sharing is typically called a "car club" in the UK and parts of Europe.

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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).[40]

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 public 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., 2022b).

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.

40 https://www.smartcitiesdive.com/ex/sustainablecitiescollective/car-sharing-picking-speed-developing-world/152996/.

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? Further, considering the lifecycle emissions from the vehicle, fuel, infrastructure, and operational services, one study finds 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). Relatedly, a study of EU cities finds that about 33% of electricity is wasted during idle time for e-scooters (Li et al., 2022).

Impacts vary by study and region, but findings generally suggest that micro-mobility is not inducing substantial GHG reductions. Consider several examples of impact analyses:

- Chengdu, China: About 39% of bike-share trips substitute for bus trips, 14% replace subway trips, and 34% replace walking (Saltykova et al., 2022).
- 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., 2022b).
- 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 gCO_2 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 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 in Canada, the US, Taiwan, Singapore, and Australia.[41]

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 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

41 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).

by 3-4% in a "conservative" scenario, 14-19% in a "balanced" scenario, and 43-54% in an "optimistic" scenario (Labee et al., 2022).

Little research has focused on MaaS for developing countries. In one survey of travellers in Manila, Philippines, 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 Barriers for shared mobility

Table 6 summarizes key barriers to the deployment of shared mobility—in particular regarding low-carbon versions of these modes. One is consumer preference for ownership and usage of private vehicles—which is true in most developed countries and increasingly true in many developing countries. For example, Canadian research finds that 20-30% of consumers are interested in using ride-hailing, 10-16% are interested in pooled ride-hailing and 12-18% are interested in car-sharing (Long and Axsen, 2022). In contrast, 30-50% are interested in privately-owned BEVs, and 30-40% in privately owned FAVs (Long and Axsen, 2022). US research has similarly found relatively low interest in pooled ride-hailing and car-sharing compared to other transport innovations (Spurlock et al., 2019). Some argue that citizens in most countries are locked into a state of "automobility", which explains both the culture and infrastructure that entrenches the dominance of privately-owned passenger vehicles (Gauer et al., 2022; Urry, 2004).

Table 6 Barriers and opportunities for shared mobility

	Barrier	Opportunities	Policies (Section 8)
1	Consumer preference	Improve consumer research (especially developing countries), improved service, education, marketing, demonstration, integration with public transit (MaaS)	Carbon/road price, incentives for usage (pooling)
2	Increasing VKM	Support pooling, integration with public transit (MaaS)	Carbon/road price, tolls for single occupancy vehicles
3	Uncertain GHG impacts	Integrate with national/regional GHG plans, pair with PEV deployment	Carbon/road price, ZEV mandate (for car-share, ride-hailing)

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Second is potential for shared mobility uptake to lead to increasing VKM, as noted in several of the shared mobility cases in this section. The use of ride-hailing or car-sharing only reduces VKM if it is replacing a low or single-occupancy mode such as driving a car, with a pooled mode. Shared mobility can thus increase VKM if it is replacing walking, cycling, or the use of public transit, or if it leads to the generation of trips that wouldn't be taken otherwise. There is also a threat from rebound effects, where a new mode that decreases the cost of vehicle travel, such as ride-hailing, would lead to more overall vehicle travel in general (Coulombel et al., 2019b). Such VKM increases could be particularly true for shared mobility in developing regions such as African countries, because they are replacing the dominant mode of walking (Sovacool et al., 2022).

Third and related are the net GHG impacts, which as noted are uncertain and found to vary widely by scenario, region, and method of analysis. Mainly, it is unclear how the introduction and expansion of a given shared mobility mode will impact private vehicle ownership, and VKM in general.

6.6 Opportunities for shared mobility

More consumer research and engagement are needed to understand how to increase the uptake of shared mobility in way that decreases VKM and private-car ownership. For example, more understanding is needed regarding how uptake could be improved by various pricing schemes and improved vehicle and system design, and how to engage consumer motives such as environmental concern (Elmashhara et al., 2022). As examples from European research, perceived ease of use can be a major motivator for uptake of car-sharing and ride-hailing (Burghard and Scherrer, 2022). Psychology factors can also matter, where interest in MaaS is associated with values and personality traits (Kim and Rasouli, 2022) and social influence (Matowicki et al., 2022). Car-sharing interest is higher among affluent, younger males, and is associated with having a tendency to share, to engage in variety-seeking lifestyle, and to have a preference for driving (Aguilera-García et al., 2022). Further research suggests that design features, such as placing bike-sharing stations in low-income neighbourhoods, can improve equity and justice impacts (Henriksson et al., 2022).

More research is also needed to study regions beyond the common cases of the US and China (Elmashhara et al., 2022), especially to understand the needs of consumers in other developing countries. 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). Research from Santiago, Chile finds that bike-sharing usage is higher with certain system characteristics, such as increased station density, and proximity of stations to offices, residences, and long cycling lanes (Mix et al., 2022).

Unique opportunities may exist in some developing countries. For examples, travelers in several major African cities already have experience and familiarity with shared mobility, such as group rapid transit, demand responsive transport systems, minibus taxis, and informal paratransit, including cities in Kenya, South Africa, Senegal, Ghana, and Nigeria (Sovacool et al., 2022). As an example, 40% of trips in Nairobi, Kenya rely on the paratransit system (Sovacool et al., 2022). That said, while uptake of functional shared mobility modes can improve welfare and accessibility in developing countries, they may lead to a net increase in VKM and GHG emissions. Further, to be successful in developing countries, shared mobility systems need to be less costly in order to address the needs of lower-income users (Sovacool et al., 2022).

To assure GHG reductions, there needs to be more push and support for pooled usage (Sperling, 2018). Consumer research in particular needs to improve understanding of how to induce use of pooled services, such as pooled ride-hailing. Research in the US finds that the price signal is important, where willingness-to-pool or use of shared ride-hailing is most influenced by trip cost, and is pooled travel is higher in areas with lower-incomes and more minorities (Taiebat et al., 2022a). Public policy could support pooled usage by incentivizing pooled trips and/or taxing single-occupancy trips.

Another avenue to reduce GHG emissions is to assure that any shared vehicle usage is electric. Analysis of US ride-hailing driver data suggests that for 86% of drivers, daily travel needs can be met by a fully charged BEV with listed range of 250 miles on at least 95% of days (Taiebat et al., 2022b). Usage of these BEV also seems likely to induce net cost savings for drivers (Taiebat et al., 2022b). 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 or cities 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.[42] Research suggest that careful integration strategies are followed, where planners need to carefully consider a given region's system characteristics and infrastructure, users characteristics and preferences, and societal impacts (Jiangping et al., 2022). MaaS in particular will have to follow careful strategies of collaboration across multiple operators in order to provide the streamlined experience desired by consumers (Bushell et al., 2022)—including collaboration between car-share and public transit operators (Vanheusden et al., 2022). Awareness campaigns can also be helpful to improve the success of shared mobility programs such as car-sharing (Vanheusden et al., 2022).

42 https://www.lvm.fi/-/improvements-to-everyday-mobility-through-act-on-transport-services-984789.

7. 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., 2018).[43] 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,[44] 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.[45] 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 regarding 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 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 FAVs, 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. Sharing seems to be particularly important; 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).

43 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.
44 Note that Tesla’s “Autopilot” feature does not yet qualify as fully-automated, as it is not SAE Level 4 or 5.
45 https://www.wired.com/story/you-own-self-driving-car/.

7.1 Barriers for automated vehicles

Several key barriers to the deployment of FAVs are summarized in Table 7. First, there is relatively little consumer demand for FAVs. Research in Canada finds that about 25% to 40% of citizens are interested in purchasing and using an FAV (Long and Axsen, 2022), with interest as high as about 50% observed in studies in China (Zhang et al., 2022), and the United States (Spurlock et al., 2019). European research finds consumers to be "wary" of FAV technology (dos Santos et al., 2022). In general, there is a great deal of consumer confusion and uncertainty about FAVs (Pudāne et al., 2019), where consumers have numerous misconceptions about FAVs (Du et al., 2022). Surprisingly, one study finds that consumers with more accurate information about FAVs tended to view the technology more negatively (Du et al., 2022).

Table 7 Barriers and opportunities for vehicle automation

	Barrier	Opportunities	Policies (Section 8)
1	Consumer confusion/preference	Education, demonstration, participatory engagement	R&D support
2	Lack of sharing	Consumer engagement, demonstrations	Carbon or road pricing, reduced parking
3	Increasing VKM		Carbon or road pricing, urban planning
4	Developing country challenges (costs and infrastructure)	Expand tech R&D in developing countries, explore sharing scenarios	R&D support

Relatedly, although many of the potential GHG benefits of FAVs come with in scenarios with shared vehicles (Vilaça et al., 2022; Wadud et al., 2016), consumers generally have less interest in shared versions of FAVs over privately owned FAVs. For example, Canadian research finds that while 33% of citizens are interested in FAVs, only 19% are interested in a shared FAV (Gauer et al., 2022). Shared FAV interest is more likely among those that have an aversion to driving, higher societal concern regarding impacts from cars, and stronger social norms for using non-car modes to get around (Gauer et al., 2022).

Another important barrier for low-carbon FAV scenarios is the potential for increasing VKM. Specifically, FAVs could increase energy use if deployment leads to 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). 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. FAV drivers may also want to drive more due to increased comfort and reduces stress (Hardman, 2021). Research with existing partially automated vehicles shows that VKM can increase by 14 to 40% among users (Asmussen et al., 2022). 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).

Finally, most developing countries are likely to face even more barriers to FAV deployment than developed countries, especially in regions with limited internet connectivity and limited or poor quality roads, as found in research in several African countries (Sovacool et al., 2022). Further, the added costs of FAV technology will increase purchase prices, which also reduces the likelihood of FAV uptake, especially among developing regions that tend to purchase used cars from other countries.

7.2 Opportunities for automated vehicles

There are of course numerous opportunities for FAVs. First, there is ample opportunity to better engage consumers in FAV research to identify use scenarios that are likely to be in demand, as well as leading to GHG reductions. As examples, consumers tend to be more interested in FAVs that still have a steering wheel to allow manual driving, and are more interested in private rather than shared FAVs (Gauer et al., 2022; Long and Axsen, 2022). The consumer research opportunities noted for shared mobility (Section 6.6) also applies to FAVs, in terms of helping to improve understanding of how to make shared usage scenarios more attractive.

Relatedly, more consumer engagement could occur at the political level. European research finds more political support to FAVs, despite consumer concern. Policymakers could better engage citizen in participatory processes regarding a transitions towards FAVs, in particular to better discuss potential benefits such as improved safety, accessibility, and mobility (dos Santos et al., 2022).

To ensure the reduction of GHG emissions, climate policy will likely have to play a strong role in FAV deployment, especially road and carbon pricing (Axsen et al., 2020; Axsen and Wolinetz, 2021). Researchers have also proposed using tolls specifically to minimize zero-occupancy vehicle usage or dead-heading (Bahrami and Roorda, 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).

Regarding developing countries, some researchers point out the potential for technological "leapfrogging", where a current technology step that is adopted in most countries is skipped by developing countries (Sovacool et al., 2022). Possibly, some developing countries that haven't yet locked-in to private ownership of conventional vehicles could bypass that technological step, leapfrogging to a scenario of shared FAVs for example. Though, considerably more research effort is needed to discover how to implement such a transition in real life. Relatedly, scenarios with shared FAVs might prove more attractive in developing countries due to the potential for costs savings per VKM or PKM—once such a system and its infrastructure are set up.

8. CLIMATE POLICY OPTIONS

This section provides a brief review and evaluation 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 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.

8.1 Policy mixes and evaluation

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). Real-world evidence indicates that policy packages have stronger impacts on PEV deployment than individual policies (Rostad Sæther, 2022)

A comprehensive policy mix analysis ought to consider policy impacts and interactions according to numerous evaluation criteria. Where evidence is available, this sections considers a policy evaluation framework proposed by Bhardwaj et al. (2020), with the following categories:

1. Effectiveness: the net impact on GHG mitigation, especially of the magnitude required to achieve deep decarbonization or net zero goals. One might also consider “co-benefits” to climate policy, such as improvements in air quality, safety, and congestion.

2. Cost-effectiveness: which is typically measured in terms of impacts to general social welfare, as well as sub-components such as consumer utility and industry profits. Policies are often compared in terms of efficiency, or dollars per tonne CO_2e.

3. Equity impacts: considers how the policy impacts different segments of society, such as consumers of different income levels or minority groups.

4. Political acceptability: includes perceptions among the public or voters (in democratic countries) and stakeholders (especially industries with political clout). Research across 33 countries suggests that perceived fairness and effectiveness are key in public acceptance of policy (Bergquist et al., 2022)

5. Transformative signal: describes support for a long-term societal and technical push towards low-carbon systems (technology and practices) (Weber and Rohracher, 2012). A policy that sends a strong transformative signal will provide confidence for industry to invest in R&D, and for other stakeholders to invest in support infrastructure.

Figure 2 Categorization of road transport policies by mitigation pathway

Policy mechanisms	Carbon Intensity (gCO_2e/MJ)	Energy Consumption (MJ/km)	Vehicle Travel Demand (km)
	Total GHH Emissions = Carbon Intensity ×	Energy Consumption ×	Vehicle Travel Demand
Mainly regulatory	Low-carbon fuel standard		
	Vehicle emissions standard	Vehicle emissions standard	
	ZEV mandate		
Mainly economic	Pricing (carbon/road/mobility)	Pricing (carbon/road/mobility)	Pricing (carbon/road/mobility)
	Financial incentives	Financial incentives	Financial incentives
Mainly systemic or information based	R&D subsidies	R&D subsidies	Info. provision
	Info. provision	Info. provision	Compact development
	Non-financial incentives		Improved public transit
	Infrastucture		Infrastucture

Source: Axsen et al., 2020.

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.

8.2 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,[46] 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). Further, carbon pricing is more likely to be effective at reducing GHG emissions if it is applied comprehensively to all sources of GHG emissions in the system, rather than just being applied to gasoline or diesel, for example. Relatedly, regions considering carbon pricing as part of their climate policy mix should also identify and remove any existing subsidies to fossil fuels that might contradict their climate mitigation goals.

Pricing can address many of the barriers noted so far in this report. Charging a substantial price on carbon emissions or fossil fuel usage can reduce vehicle ownership and VKM. In particular, including pricing in a policy mix can help to 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., 2019a). The presence of a strong, long-term carbon price can help to channel the development of automation and shared mobility technologies towards the versions that reduce VKM. Carbon pricing is also found to be a complement to public transit deployment, as the combination of price signal and increased

46 Cordon pricing is the application of a charge to drive into a particular area, say the downtown zone of a city.

public transit choice can lead a more substantial low-carbon shift in the market (Gibson and Carnovale, 2015; Gillingham and Munk-Nielsen, 2019). Others suggest that because ZEVs tend to be heavier than conventional ICE vehicles, to further improve efficiency future road or vehicle taxes should be partially based on vehicle weight (Galvin, 2022; Shaffer et al., 2021).

Pricing is likely to be effective in developing countries as well. One simulation modeling study in Rio De Janeiro, Brazil finds that carbon pricing is the most efficient and effective way to cut GHG emissions, provided that zero-carbon public transport is also expanded (Silva et al., 2022). That said, a study of Colombia finds that while a carbon tax can help to reduce light-duty vehicle emissions, it comes at a relatively high social costs that might reduce political acceptability (Callejas et al., 2022).

The major challenge of pricing are public acceptability and equity impacts. As found consistently across studies in different countries, pricing mechanisms evoke significantly 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). For example, Canadian research shows that citizen opposition to a $50/tonne or $150/tonne carbon prices is more than double the opposition to any other light-duty vehicle climate policy, including a vehicle emissions standard (VES), low-carbon fuel standard (LCFS), ZEV mandate, purchase subsidy, or charger deployment (Long et al., 2021).

Another challenge is equity impacts. Depending on region and policy design pricing, can be found to be regressive, that is, hurting lower income households or progressive, having more impact on higher-income households (Levinson, 2010). Equity impacts can be affected by the programs use of tax revenues and exemptions. For example, using revenues for income tax cuts will provide greater benefits for high-income people, while using revenue for transit improvement brings a greater benefit to low-income people and women (Eliasson and Mattsson, 2006). More research is need on developing countries to understand how to best design pricing mechanisms in contexts with higher poverty levels, and also how to best complement existing public transit and active travel options.

Finally, a carbon tax tends to send a weaker transformative signal compared to other policies. Because a tax is technology neutral, any induced innovation activity may be spread out across multiple technologies rather than triggering a breakthrough in one technology (Fox et al., 2017).

8.3 Market-oriented regulations

A second broad category is market-oriented regulations, which provides 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. In contrast “pure” or “command-and-control” regulation enforce the same technology requirement on every regulated agent, with no credit trading, and little or no choice among compliance options.

Three regulations in particular are increasing in popularity, while also showing promise for effectiveness in reducing GHG emissions (Axsen et al., 2020): a ZEV sales mandate, an LCFS, and a VES. 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).

First, a ZEV sales mandate 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 ZEV mandates are now being updated to transition into an ICE ban, or 100% ZEV requirement, by 2035 or earlier. ZEV mandates have been shown to play an important role in GHG mitigation targets (Sykes and Axsen, 2017), while addressing several of the barriers identified for PEVs and FCEVs (Axsen et al., 2022). The policy has been effective in channeling innovation activities towards ZEV development (Sierzchula and Nemet, 2015; Wesseling et al., 2015), which can bring down costs more quickly than a technology neutral policy (Fox et al., 2017). It also induces automakers and dealerships to improve ZEV marketing and increase the availability of ZEVs for sale (Bhardwaj et al., 2021; Slowik and Lutsey, 2018), which can also help to increase consumer preferences for ZEVs (Axsen et al., 2009). Certain design features can make a ZEV mandate more effective and efficient, such as having large enough penalties for non-compliance and allowing automakers to bank credits over multiple years (Bhardwaj et al., 2022).

Second, a vehicle emissions standard (VES) 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). Typically, the performance requirement is set as an average for the vehicle fleet. As with a ZEV mandate, a VES generally is found to be effective, and can be part of a relatively cost-effective policy mix, especially if combined with carbon pricing (Small, 2012). Further, a strong enough VES may have the same impact as a strong ZEV mandate, if in practice the policy can be complied with via increased ZEV sales. In that sense, a strong VES can address many of the same PEV and FCEV barriers as a ZEV mandate.

Third, a low-carbon fuel standard (LCFS) 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), accounting for different feedstocks or sources. Typically, compliance credits are tradeable among fuel suppliers, including electric utilities (Yeh et al., 2016). Modeling studies indicate that an LCFS can play an important role in a climate policy mix for light-duty and heavy-duty vehicles—in particular by making sure that investment goes into only low carbon forms of electricity, hydrogen, and biofuels (Lepitzki and Axsen, 2018). If designed carefully, an LCFS can thus support coordination of ZEV development with smart charging that connects to renewable electricity sources, and also investment in green and blue hydrogen. With a well-designed LCFS, investment in biofuels will also be channeled towards low-carbon feedstocks and refinement processes, accounting for indirect land-use change and any other potential negative environmental impacts.

Because each regulation is technology focused, strong versions of each policy can send a strong transformative signal for long-term investment in low-carbon vehicles, fuels, and supporting infrastructure (Melton et al., 2020). 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, while establishing credibility and trust that the policy will stay in place over time (Bhardwaj et al., 2021; Sierzchula and Nemet, 2015).

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). The VES and LCFS in particular are supported by 55% to 80% of citizens in these countries (Long et al., 2020). However, less is known about the equity impacts because research is limited. Such policies are likely to increase the overall cost of vehicles and fuel, which may have a relatively more negative impacts on lower-income households. As with carbon and road pricing, equity could be improved through careful policy design, such provision of exemptions or purchase refunds for lower-income buyers.

Although versions of these policies have proven effective in several developed countries as well as China, less known about their suitability for developing nations. Some countries, such as India, have ambitious goals to achieve 100% ZEV sales—but it is not clear if these regulations are the best way to achieve these goals, nor how to optimize regulation design to best meet the needs of developing countries.

8.4 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). Incentives address one of the most basic barriers to PEV and FCEV adoption – the high purchase costs—which can make ZEVs more attractive to households and firms alike. 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). 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). Some research has explored the optimal timing to phase out ZEV purchase incentives, for example with study of China suggesting a 2025 phase out of incentives, but only if replaced with a n ICE sales ban in that year (Wang et al., 2022a).

Generally speaking, such incentives tend to have high public acceptability (Long et al., 2021; Melton et al., 2020; Rhodes et al., 2017). They are generally a less cost-effective policy, with the potential for inequitable outcomes, namely by using tax payer dollars to provide savings to the higher-income households that can afford ZEVs (DeShazo et al., 2017). Though, equity 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; Linn, 2022). Interestingly, research in the US and Japan finds that consumers are more supportive of ZEV subsidies that are available to all buyers, not just lower-income buyers (Lim et al., 2022).

“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). That said, Norway has found them to play an important role in their world-leading strategy to support BEV uptake (Figenbaum, 2017; Rawat et al., 2021).

As with other climate policies, most of the research on ZEV purchase incentives is focused on the US, Canada, Europe, and China. Less is known about the potential role of incentive strategies on developing countries, where there is likely to be less funds available for governments to spend. Lower-income regions may want to explore more revenue-neutral strategies, such as a "feebate" scheme that puts a purchase tax on high emissions vehicles, and uses revenue to provide a subsidy for low emissions vehicles and ZEVs (Durrmeyer and Samano, 2018). As one example, Taiwan has provided subsidies worth about $USD 100 to 400 for the purchase of e-scooters and electric motorcycles, which are thought to send a strong transformative signal to manufacturers (Rawat et al., 2021).

8.5 Deployment of charging and fueling infrastructure

Limited charging and fueling infrastructure represent important barriers for PEVs and FCEVs. Policy mixes thus need to support the rollout of electric- and hydrogen-based infrastructure. Initiatives can include government sponsored charger and fueling stations, building standards that require charging infrastructure, and financial incentives for infrastructure installation. For light-duty PEVs, improvements to home charging opportunities typically have 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). Expanding PEV charging infrastructure can also help to address the social barriers to ZEV uptake, such as by setting subjective norms or social pressures regarding the usage of PEVs (White et al., 2022). 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).

Heavy-duty vehicles face even greater charging infrastructure barriers, which may require more advanced technology such as megachargers and catenary systems. Research suggests that while PEVs are more likely to succeed as light-duty ZEVs, the deployment of long-haul heavy-duty ZEVs are more likely to follow whichever infrastructure is supported, be it hydrogen or electricity (Lajevardi et al., 2022).

Infrastructure deployment is likely to positively complement any policy mix, by increasing the efficacy of regulations and pricing. It also tends to be politically acceptable (Long et al., 2021), while helping to send a transformative signal about the direction for future technological change. That said, unused or poorly designed infrastructure systems may have a negative impact on citizen perceptions, and hamper a ZEV transition.

Less research has focused on how to best deploy charging and fueling infrastructure in developing countries—though lack of infrastructure is clearly an important barrier (Rawat et al., 2021). As some examples:

- China has focused more heavily on charging infrastructure and has deployed over 1.2 million chargers nationally (Rawat et al., 2021).
- Korea has set up several incentives for private charging stations, covering installation costs, rent of public land, and loan guarantees
- India's government has been working to set up clear guidelines and standards for PEV charging stations, while also providing incentives for station installation (Rawat et al., 2021).

8.6 Research and development subsidies

A final policy category in this area is public support for research & development (R&D) and related innovation activities. The intent is to support such innovation, while sending a transformative signal to other stakeholders to also invest in low-carbon technology, such as private industry, with the ultimate goals of bringing down technology costs and improving performance. If successful, such R&D activities could help to address many of the barriers noted earlier, including high up front purchase prices, limited availability, and limited consumer demand.

R&D subsidies can support technology advancements in any of the deep decarbonization technologies noted in this report, including improvements in advanced batteries (cost and performance), fuel-cell technology, megachargers, catenaries, advanced biofuels, forms of shared mobility, and automation technology. However, given the private and long-term nature of R&D, it is difficult to trace long-term trends in investment, and to identify a causal impact on technological breakthrough. Some general lessons from the past suggest that R&D support for alternative fuels has not been 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). Further, research on renewable energy R&D subsidies in China suggest that while the subsidies do boost transformation, there may be a limit to their efficacy as some private firms will free-ride and reduce the amount of R&D spending that they would otherwise spend (Qi et al., 2022)

One related goal is for governments to try to set up and support domestic industries for low-carbon transportation, especially for developing nations. If successful, this could increase the within-country supply of the technology, and perhaps support economic growth via domestic and international demand. Both Korea and China have substantially supported domestic development of advanced battery technology, where China in particular now produces more than two-thirds of global lithium-based batteries (Rawat et al., 2021). Korea has invested millions in R&D projects for FCEV and BEV components, which corresponds with the magnitude of private investment (Rawat et al., 2021). India is also seeking to set up large domestic industries for battery manufacturing, and Ghana has had some success with domestic e-mobility businesses that locally assemble PEVs (Rawat et al., 2021). Other developing countries are looking to invest in and develop existing resources, such as Zimbabwe's lithium deposits (Rawat et al., 2021).

A key recommendation is that R&D subsidies should be carefully planned as part of a broader climate policy mix and coordinated with private industry and other stakeholders to maximize the complementary impacts of any induced innovation activities.

9. KEY FINDINGS AND POSSIBLE ACTIONS

9.1 Summary

This analysis is focused on the technology readiness of the case technologies, as well as market progress and potential for GHG reductions. 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. Key barriers to further deployment remain, including relatively high purchase prices, limited charging opportunities, impacts to the grid, impacts from batteries, limited availability, and limited consumer awareness and preferences. However, there are many opportunities to address these barriers through various stakeholder efforts, especially public policies such as a ZEV sales mandate, low-carbon fuel standard, support for charger deployment, and purchase incentives. Heavy-duty PEVs face some stronger technological barriers for most applications, notably the added challenges of driving range and charging infrastructure.

Readiness is lower for FCEVs (TRL 8), which has more extreme versions of the barriers noted for PEVs, such as very high purchase costs for light-duty and heavy-duty applications, and strong limitations in refueling infrastructure, model availability, and consumer demand. The production of “green” or “blue” hydrogen needs to be substantially improved and expanded for this technology to play a role in deep decarbonization scenarios. Various opportunities and policies can help with FCEV development, though PEVs seem likely to outcompete FCEVs in most road transport applications, except perhaps for long-haul heavy-duty.

Readiness for advanced biofuels is also relatively low (TRL 7-9). It has proven challenging to improve low-carbon ethanol and biodiesel, while also avoiding negative impacts to food prices and food security. There is a potential advantage given that these fuels can be used in blends with existing gasoline or diesel-based engines, especially “drop-in” fuels such as HDRD. However, the development and market penetration of low-carbon or advanced 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, it is unclear if consumer preferences in most countries can be shifted away from private vehicle ownership. In a sense, the biggest barrier to the low-carbon versions of these modes is that there is no clear evidence of a net carbon benefit, nor of substantially displacing ownership of private vehicles.

Finally, vehicle automation is in a very early stage 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 low-carbon automation scenarios. Key barriers to deployment of low-carbon versions of automation include consumer confusion about the technology, and continued consumer preference for private rather than shared versions of automation.

This report also evaluates 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 (R&D). Evidence is summarized for each regarding effectiveness in reducing GHG emissions, cost-effectiveness or efficiency, equity impacts, political acceptability, and transformative signal. The report also considers the ability of each policy type to address the barriers noted above.

The next sections consider key messages and possible actions for technology support and public policy implementation, followed by consideration of directions for future work.

9.2 Key findings and possible actions to accelerate the uptake of technologies for sustainable road mobility

Drawing from the evidence reviewed in this report, this report offers a number of key messages and possible actions that are relevant to policymakers, industry, and other stakeholders seeking to achieve deep decarbonization or net zero goals through accelerating the uptake of technologies for sustainable road mobility.

1. **PEVs offer the highest technology readiness and low-carbon potential for light-duty vehicles, as well as some medium-duty and heavy-duty applications**. That said, the technology still needs policy and stakeholder support to overcome technical and social barriers, and to achieve the adoption rates that align with deep decarbonization and net zero goals. In most countries, policymakers will want to prioritize PEVs as a key GHG emissions mitigation technology for the road transportation sector. In many developing countries, PEVs might have a stronger opportunity for two- and three-wheeler applications.

2. **Hydrogen and advanced biofuels have lower technology readiness and higher adoption barriers than electrification, and are not expected to play as large a role in deep decarbonization of road transportation**. Policymaker and industry support should continue for the most promising applications, notably long-haul heavy-duty FCEVs. Advanced biofuels could also play a smaller decarbonization role through blending into fossil fuel mixes, or the development of “drop-in” fuels such as HDRD.

3. **ZEV deployment needs to be aligned with support for low-carbon fuels, namely zero-emissions electricity, green or blue hydrogen, and/or advanced biofuels**. When creating a climate mitigation plan or blueprint, policymakers that are serious about deep decarbonization goals will want to use up-to-date calculations of well-to-wheel or fully lifecycle emissions, and to include such considerations in the design of policy mixes. In particular, policymakers may consider a low-carbon fuel standard (LCFS) that regulates transportation fuels based on lifecycle GHG emissions impacts.

4. **More research and policy effort is needed to improve the sustainability impacts of ZEV manufacturing and disposal, including extraction of metals for advanced batteries, and battery end-of-life reuse or recycling**. Similar to the previous finding, policymakers will want to consider and address the GHG emissions and other sustainability impacts associated with ZEV manufacturing. More government policy and industry investment is needed to better understand and mitigate these impacts, such as supporting the development of battery chemistries that don't rely on higher impact materials. Effective development of battery re-use and recycling can further reduce the lifecycle impacts of PEVs.

5. **Shared mobility is likely to play a small role, if any, in deep decarbonization**. To help with climate goals, policymakers need to support shared mobility in ways that help to reduce vehicle travel (VKM) and vehicle ownership. The most promising pathways are through increased use of pooling, such as pooled-ride-hailing, as well as coordination to improve public transit service and uptake, such as MaaS. However, evidence to date suggests that consumer preference for private vehicle ownership and private rides will be difficult to shift.

6. **Vehicle automation is a highly uncertain set of technologies that could increase or decrease GHG emissions**. Strong government policy is needed to guide the development of FAVs in a low-carbon direction, in particular to increase the focus on improved efficiency, pooling, and reduced VKM. Strong road or carbon pricing can be particularly effective in this regard, as well as land-use policy that prevents further urban sprawl.

9.3 Potential actions for policymakers

The policy evaluation provided in Section 8 identifies a number of potential policymaker actions to support the development and adoption of these low-carbon technologies. Overall, evidence indicates that a coherent policy mix is most likely to be successful in addressing multiple policy evaluation criteria and barriers to technology uptake. Important knowledge gaps remain as to how to best implement an effective policy mix in developing countries.

From the available evidence, market-oriented regulations such as low-carbon fuel standards, vehicle emissions standards, and ZEV sales mandates can provide a balance of effectiveness and political acceptability, while sending a clear transformative signal to industry and stakeholders. Other policies can play supportive roles in an effective policy mix. While pricing can be the most cost-effective policy, it tends to suffer from high political opposition at the high stringency needed to be effective. Purchase incentives can boost ZEV sales but are costly to governments in the long-run. Deployment of charging infrastructure and fueling infrastructure can also support strong regulations in achieving 100% ZEV sales goals.

From this evaluation, several potential policy actions are identified:

1. **Plan out policies as a complementary mix that fits a regional context**. All examples of effective or successful climate policies for road transportation include a suite of policy. One reason is that the deep carbonization technologies in this sector face a diverse set of technical and social barriers. Further, policies can offer different and complementary benefits to a policy mix, including not only the ability to induce further GHG emissions reductions, but also to potentially improve policy cost-effectiveness or efficiency, equity, political acceptability, and/or transformative signal. The mix of policies should be coordinated in a way to maximize complementarity regarding these evaluation criteria.

2. **Focus on a ZEV sales mandate where possible**. This policy has been shown to effectively induce increased ZEV availability and sales in a given region, while channeling R&D and innovation activity towards ZEV technology. A well-designed version of a ZEV mandate could play a lead role in a country's policy mix, where financial penalties for automaker non-compliance would add "teeth" to the ambitious ZEV sales goals and ICE bans that many countries are announcing. Alternatively, a strong vehicle emissions standard (VES) could have a similar effect on ZEV technology and sales as a ZEV mandate. There are several existing examples for the light-duty vehicle sector, and some regions are starting to implement versions for medium- and heavy-duty vehicles as well.

3. **Support low-carbon fuels through a low-carbon fuel standard (LCFS)**. Because this policy sets fuel sales requirements based on the lifecycle GHG emissions of fuels, it sends a transformative signal for investment into low-carbon electricity, blue and green hydrogen, and advanced biofuels. It is thus can play a key role in a policy mix, complementing the deployment of ZEVs by assuring that low-carbon fuels are developed and utilized.

4. **Carbon or road pricing should be included in a policy mix, subject to acceptability**. Pricing policies can be cost-effective, while also helping to reduce VKM and vehicle ownership. When added to a policy mix with regulations, pricing can improve the cost-effectiveness of the mix. The main challenge is political acceptability, where an overly high price could lead to considerable public and industry opposition. Another challenge is equity impacts, though these can be improved through careful use of revenue recycling, such as using funds to support public transit or provision of other subsidies that target low-income or otherwise disadvantaged households. Pricing can also be an effective complement to deployment of shared mobility and vehicle automation, to support goals to reduce VKM and vehicle ownership.

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5. **ZEV purchase incentives can be helpful but can be expensive for governments**. Evidence shows that although incentives can boost sales, they will likely be needed for the long-term in the absence of strong regulation. To make careful use of taxpayer money in the long-term, governments may want to consider revenue neutral designs, such as using carbon, road, or conventional vehicle taxes to generate revenues that fund ZEV purchase incentives. Setting caps on vehicle price and household income can also improve the equity effects of ZEV purchase subsidies. As part of a longer-term strategy, purchase subsidies could be viewed as an initial, short-term complement to strong regulations such as a ZEV mandate and LCFS, helping automakers, fuel suppliers, and consumers to adjust to the first few years of transition before subsidies are gradually phased out.

6. **Charging and refueling infrastructure needs to be supported to achieve widespread ZEV sales**. Policies can include government sponsored charger and fueling stations, building standards that require charging infrastructure, and financial incentives for infrastructure installation. Advanced technologies will be needed to support full decarbonization, especially for heavy-duty applications, notably with further support for megachargers, catenaries, and/or hydrogen refueling.

7. **Governments can further guide low-carbon innovation with direct R&D support, in addition to the above noted policies**. The already noted regulations can send a strong transformative signal for private industry to channel R&D and innovation efforts into ZEV technology. The offering of direct R&D subsidies could help to further channel domestic innovation activities, though governments should beware of free-ridership among firms, while also being careful about the opportunity costs of this type of spending—that is, if the funds could be more efficiently spent on other climate mitigation efforts. Careful program development is needed, especially through private-public partnerships to assure that taxpayer funds are being spent carefully and effectively.

8. **Improved institutional capacity is needed for effective implementation and adaptation of a climate policy mix**. To design, assess, enforce, and maintain these policy mixes, most governments need to ensure they have the needed institutional capacity. This may include the development of research-oriented institutions that track the various low-carbon technologies reviewed here, including progress regarding social and technical barriers, as well as lessons learned for the design of a climate policy mix. California has provided a particularly effective example of an effective and durable policy institution with the California Air Resource Board (CARB).

9.4 Potential future work

While this report summarizes available evidence regarding deep decarbonization technologies for road transportation, and supportive public policies, it also identifies key knowledge and research gaps. Future work in this area may want to prioritize improved understanding on a number of topics in this field, including:

- Optimal design of climate mixes for developing countries, especially the use of market-oriented regulations.
- Effective strategies to build institutional capacity for deep decarbonization and climate policy implementation, especially in developing countries.
- Further exploration of the unique needs for medium-duty and heavy-duty road vehicles, especially charging and hydrogen (or advanced biofuel) refueling infrastructure for long-haul applications.
- More specifically, how and in what context to prioritize support for hydrogen and FCEVs over PEVs.
- Strategies to reduce vehicle ownership and VKM in both developed and developing country contexts.
- Strategies to lessen the GHG and sustainability impacts of ZEV manufacturing and disposal, including policy and investment support for new battery chemistries and battery recycling.

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TEC

About the Technology Executive Committee

The Technology Executive Committee is the policy component of the Technology Mechanism, which was established by the Conference of the Parties in 2010 to facilitate the implementation of enhanced action on climate technology development and transfer. The TEC analyses climate technology issues and develops policies that can accelerate the development and transfer of low-emission and climate resilient technologies.

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