Global Electrification of Light-duty Vehicles: Impacts of Economics and Climate Policy

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ABSTRACT

We explore potential impacts of global decarbonization on trends in light-duty vehicle (LDV) fleets from 2020-2050. Using an economy-wide multi-region multi-sector model, we project that the global EV fleet will grow from 5 million vehicles in 2018 to about 95-105 million EVs by 2030, and 585-823 million EVs by 2050. At this level of market penetration, EVs would constitute one-third to one-half of the overall LDV fleet by 2050 in different scenarios. China, USA, and Europe remain the largest markets in our study timeframe, but EVs are projected to grow in all regions reducing oil use and emissions. EVs play a role in reducing oil use, but a more substantial reduction in oil consumption comes from economy-wide carbon pricing. Absent more aggressive efforts to reduce carbon emissions, global oil consumption is not radically reduced in the next several decades because of increased demand from other sectors, such as for heavy-duty transport and non-fuel uses. Overall, we find that EVs, along with more efficient ICEVs, represent a viable opportunity among a set of options for reducing global carbon emissions at a manageable cost.

Keywords: Light-duty vehicles, electric cars, climate policy, oil use, carbon dioxide emissions.

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1. INTRODUCTION

The United Nations (UN) Paris Agreement established a goal of limiting the global average surface temperature to "well below 2°C" relative to pre-industrial levels (UN 2015). Achieving this target requires a substantial reduction in greenhouse gas (GHG) emissions by mid-century and moving to net-zero GHG emission towards the end of the century (IPCC 2014) or even earlier, by mid-century, for reaching the 1.5°C target (IPCC 2018). Electrifying transport sector coupled with decarbonization of electricity offers a pathway to reach the goals of the Paris Agreement. Currently, electrification is mostly occur in the private light-duty (that is, cars and light trucks) vehicles (LDV) segment and in 2018 the global electric car fleet exceeded 5.1 million (IEA 2019).

In this paper, we use an enhanced version of the MIT Economic Projection and Policy Analysis (EPPA) model (Chen et al. 2016, Ghandi and Paltsev 2019, 2020) to explore the potential impacts of global decarbonization on trends in the LDV fleet from 2020-2050. In particular, we assess the changes in LDV fleet composition, fuel consumption, electricity production, CO_2 emissions, and macroeconomic impacts (including the cost of avoided CO_2

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emissions). Using a scenario-based approach, we perform the analysis for 18 different regions of the world. We provide the results for penetration of different types of LDVs up to 2050 for the scenario based on the current market trends and fuel efficiency policies, for the scenario where the Paris Agreement commitment are not strengthened after 2030, and for the scenario where decarbonization actions are enhanced to be consistent with limiting global average surface temperature to 2°C relative to preindustrial levels. Our results and findings can help stakeholders anticipate and navigate the challenges that lie ahead.

The scenarios considered in this paper show some potential trajectories for achieving low emission goals. Realization of the aggressive emission mitigation scenario would need a substantial increase in policy development and coordination in comparison to the current path of country-specific actions. However, it is possible that even more aggressive actions are necessary, which would call for a faster transition to low-emitting options than in our scenarios. Our paper will help decision makers to design efficient pathways to reduce emissions.

The paper is organized in the following way. In Section 2 we provide a brief description of the EPPA model and the explored scenarios. In Section 3 we present both global and regional impacts of global climate change mitigation on internal combustion engine vehicle (ICEV) and electric vehicle (EV) stock, CO_2 emissions, and fuel consumption and prices. We also discuss implications for macroeconomics and government revenues. In Section 4 we consider key sensitivities surrounding the penetration of EVs in the LDV fleet. We then summarize our findings in Section 5.

2. THE EPPA MODEL AND SCENARIOS OF ECONOMIC AND POLICY DEVELOPMENT

The MIT Economic Projection and Policy Analysis (EPPA) model (Paltsev et al. 2005; Chen et al. 2016) is a dynamic multi-region multi-sector computable general equilibrium (CGE) model. It offers an analytic tool that includes a technology-rich representation of the household transport sector and its substitution with purchased modes, as documented in Karplus et al. (2013). The model captures interactions between all sectors of the economy, accounting for changes in international trade. Data on production, consumption, intermediate inputs, international trade, energy and taxes for the base year are from the Global Trade Analysis Project (GTAP) dataset (Aguiar et al. 2016). The GTAP dataset is aggregated into 18 regions (Figure 1).

The EPPA model has 34 sectors (Table 1), including several advanced technology sectors parameterized with supplementary engineering cost data (Morris et al. 2019). Economic growth by region for 2010-2020 is calibrated to historic data and short-term projections from the International Monetary Fund (IMF 2019). Energy use by region for 2010-2015 is calibrated to data from the International Energy Agency (IEA 2018). From 2020, the model solves at 5-year intervals. The model includes a representation of the household transport sector and its substitution with purchased modes of public transportation, including aviation, rail, and marine transport (Paltsev et al. 2004). Several features were incorporated into the EPPA model to explicitly represent household transport sector detail (Karplus et al. 2013, Ghandi and Paltsev 2019). These features include an empirically-based parameterization of the relationship between income growth and demand for vehicle miles traveled (VMT), a representation of fleet turnover, and opportunities for fuel use and emissions abatement, including representation of electric vehicles. Additional information about the details of the EPPA model can be found in Chen et al. (2016), Paltsev et al. (2018) and Ghandi and Paltsev (2019, 2020).

FIGURE 1
EPPA Model Regional Coverage.

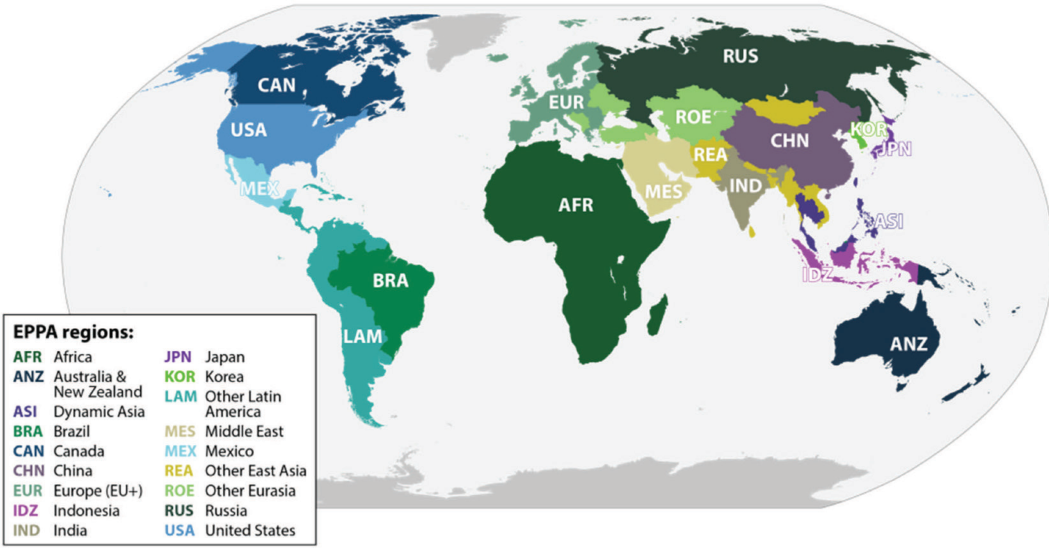


TABLE 1
Sectors in the EPPA model

Sectors	Abbreviation	Sectors	Abbreviation
Energy-Intensive Industries	EINT	Coal Electricity	ELEC: coal
Other Industries	OTHR	Natural Gas Electricity	ELEC: gas
Services	SERV	Petroleum Electricity	ELEC: oil
Crops	CROP	Nuclear electricity	ELEC: nucl
Livestock	LIVE	Hydro Electricity	ELEC: hydro
Forestry	FORS	Wind Electricity	ELEC: wind
Food Processing	FOOD	Solar Electricity	ELEC: solar
Coal Production	COAL	Biomass Electricity	ELEC: bele
Oil Production	OIL	Wind combined with gas backup	ELEC: windgas
Refining	ROIL	Wind combined with biofuel backup	ELEC: windbio
Natural Gas Production	GAS	Coal with CCS	ELEC: igcap
Synthetic Gas from Coal	SGAS	Natural Gas with CCS	ELEC: ngcap
Commercial Transportation	TRAN	Advanced Nuclear Electricity	ELEC: anuc
Private Transportation: Gasoline & Diesel Vehicles	HTRN: ice	Advanced Natural Gas	ELEC: ngcc
Private Transportation: Plug-in Hybrid Vehicles	HTRN: phev	First-Generation Biofuels	BIOF
Private Transportation: Battery Electric Vehicles	HTRN: bev	Advanced Biofuels	ABIO
Private Transportation: Hydrogen Vehicles	HTRN: fcev	Oil Shale	SOIL

The GTAP data, which is the source for the underlying data for the EPPA model in a base year, does not provide the details on household transportation. To calibrate the EPPA model, additional data on the stocks of private light-duty vehicles, expenditures on fuel, vehicle and services, cost of alternative vehicles were used as described in Ghandi and Paltsev (2020). The electric vehicle (EV) category in our analysis includes plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEV).

To assess trends in the light-duty vehicle (LDV) fleet over the 2020–2050 timeframe, we modeled three policy scenarios: (1) the *Reference* scenario; (2) a *Paris Forever* scenario, which assumes implementation of commitments under the Paris Agreement by 2030 and continuation of those policies thereafter, but no additional policy action; and (3) a *Paris to 2°C* scenario, which assumes policy action beyond current Paris commitments to ensure that the increase in Earth's average surface temperature (relative to pre-industrial levels) does not exceed 2°C. Later sections describe key results of the modeling analysis for each scenario.

Our *Reference* scenario assumes continued strengthening of fuel efficiency standards for LDVs, as well as expanded use of renewables for power generation (IEA 2017). It does not include mitigation pledges made by countries in their submissions for the Paris Agreement (UN 2015). Growth in population and economic activity (as measured by gross domestic product or GDP) are the key drivers of changes in future demand for mobility. For population growth, we adopt a central estimate from the United Nations (UN 2017), which projects that the world population will increase from 7.8 billion in 2020 to 9.8 billion in 2050. The fastest growth is expected to occur in Africa, the Middle East, and Australia/New Zealand, where the model assumes average annual population growth rates of 2.1 %, 1.2 %, and 1 %, respectively, over the 2020–2050 timeframe. Some countries, such as Japan, Russia, China, and South Korea, are projected to experience negative population growth over this period.

For near-term GDP growth, we rely on forecasts from the International Monetary Fund (IMF 2019), and then follow assumptions about long-term productivity growth from the MIT Joint Program Outlook (MIT Joint Program 2018). This results in an assumed world GDP average annual growth rate of about 2.6 % for the 2020–2050 study period. We assume slower growth in advanced economies than in developing economies (see Appendix C). For example, average annual GDP growth between 2020 and 2050 is modeled at 1.7 % in Europe and Japan and about 2 % in the U.S., while GDP for China, India, Africa, and East Asia is assumed to grow at an average annual rate of about 4.0–4.5 % during that period. Global economic growth slows from about 2.9 % in 2020 to about 2.35 % in 2050.

The average fuel efficiency of the LDV fleet varies by region, with Europe, Japan, and the U.S. having the most fuel-efficient ICEV fleets—averaging 24–26 miles per gallon (MPG)—in 2015. To model future gains in LDV fuel efficiency, we assume that fuel efficiency standards increase in all regions by 1–2 % per year. In the U.S. and Europe, standards are assumed to increase by 1.4 % per year, in China by 1.3 % per year, and in India by 1.1 % per year. In most developing economies, the assumed increase is faster (close to 2 % per year), bringing fleet efficiency in these countries closer to that of advanced economies. For the U.S., our assumptions are driven by the assessments of the U.S. Energy Information Administration (EIA) (2018). For other regions, we rely on a study by Karplus et al. (2015).

Our *Paris Forever* scenario assumes that the country-level commitments pledged under the Paris Agreement are met by 2030 and retained thereafter (see Appendix A for the modeling implementation of nationally determined contributions or "NDCs" under the Paris Agreement). While we assume the same population growth in all scenarios, GDP growth is affected by economic and climate policies and is different in different policy scenarios. For the *Paris Forever* scenario we explore additional cases that assume lower global costs for EV technology and higher demand for private transportation in China.

Our *Paris to 2°C* scenario assumes the same mitigation efforts as the *Paris Forever* scenario up to 2030, but more aggressive policy action thereafter to reach the global emissions trajectory needed to limit global average surface temperature warming to 2°C. We assume mitigation is achieved through global economy-wide carbon pricing after 2030, with emission profiles from Sokolov et al. (2017) that are based on the MIT Integrated Global System model results. In this scenario, after achieving their NDC targets for 2030, all countries impose carbon prices that are rising to about \$140/tCO_2 in 2040 and to about \$200/tCO_2 in 2050. For this scenario we consider additional cases that assume lower EV costs and higher levels of support for the deployment of renewable energy. We also test a case in which fuel-cell electric vehicles (FCEV) running on hydrogen comprise 5 % of the LDV fleet in the U.S. In addition, we consider a scenario with increased global emission mitigation ambitions.

3. GLOBAL AND REGIONAL IMPLICATIONS

In all scenarios, growth in economic activity and population drive a substantial increase in the global stock of LDVs (we use the terms "vehicle fleet" and "vehicle stock" interchangeably)—from approximately 1.1 billion vehicles in 2015 to an estimated 1.65–1.75 billion vehicles in 2050 (Figure 2). In the *Reference* scenario, the global stock of LDVs is close to 1.4 billion vehicles in 2030 and about 1.75 billion vehicles in 2050. The implementation of climate-change mitigation policies in the *Paris Forever* and *Paris to 2°C* scenarios affects fuel prices, vehicle efficiency, income levels of consumers, and their demand for transportation. As a result, the global stock of LDVs in 2030 is about 30 million vehicles smaller in both the Paris scenarios compared to the *Reference* scenario. After 2030, the more aggressive carbon constraints in the *Paris to 2°C* scenario have a further dampening impact on LDV fleet growth worldwide. Our modeling results for 2050 show 40 million fewer vehicles globally in the *Paris Forever* scenario compared to the *Reference* scenario. The corresponding reduction in the *Paris to 2°C* scenario is about 125 million vehicles.

In all scenarios, the LDV stock grows in all regions. Figure 3 shows results for regional LDV stocks in the *Paris Forever* scenario (Appendix B provides more detail about which countries are included in different EPPA regions). Europe (EUR), the U.S. (USA), and China (CHN) are the regions with the largest LDV fleets in 2015 (see Ghandi and Paltsev (2019) for

FIGURE 2
Global LDV stock.

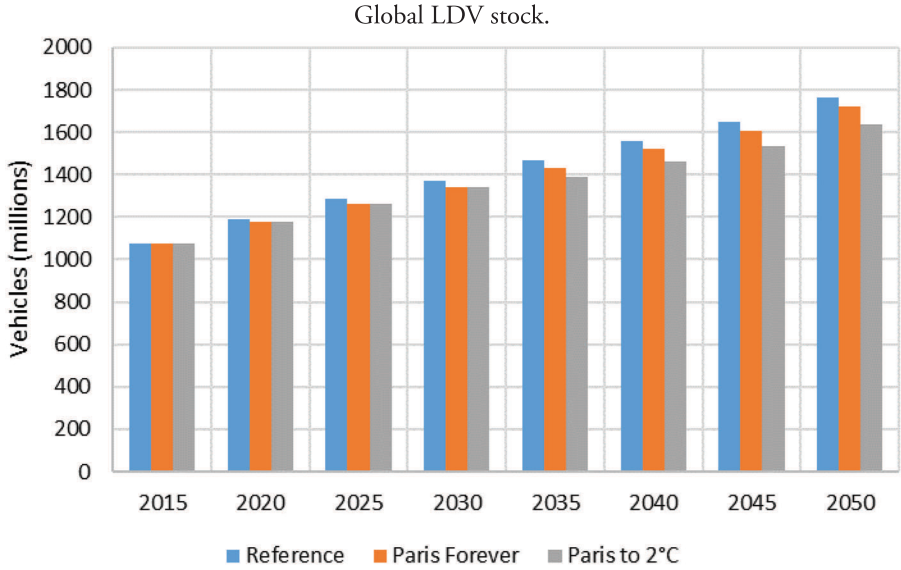
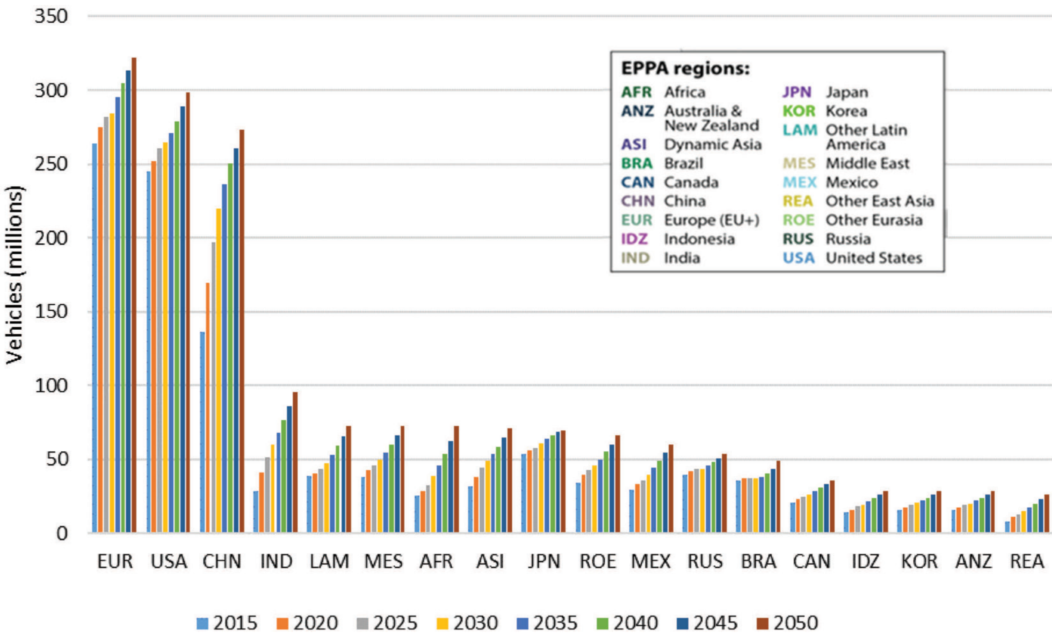


FIGURE 3

Regional LDV stock in the Paris Forever scenario.



a discussion of historic data). These regions continue to have the largest fleets over the study period (in 2050, their combined share of the global LDV fleet is more than 50 %). However, there are differences in the rate of fleet growth between regions. For Europe and the U.S., the model predicts a 22 % increase in number of LDVs between 2015 and 2050; in China, by contrast, projected fleet growth over this period is about 100 %. As a result, the model projects about 320 million vehicles in Europe, about 300 million vehicles in the U.S., and about 275 million vehicles in China in 2050 under the *Paris Forever* scenario.

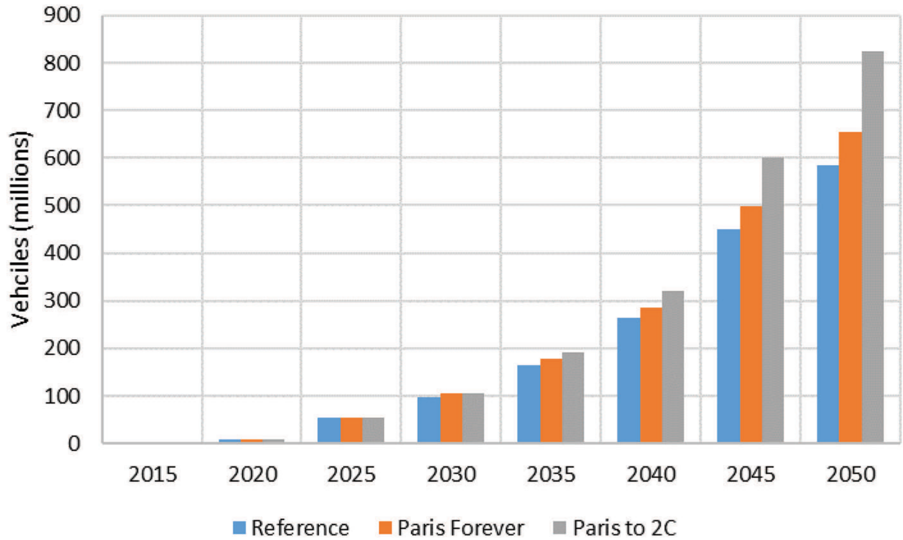
Some regions experience even faster fleet growth than China, but they start from a smaller base. In India (IND), the LDV fleet is projected to grow 230 % by mid-century, from about 30 million vehicles in 2015 to close to 100 million vehicles in 2050. Projected fleet growth in the rest of East Asia (denoted REA in the figure) is 210 %, from about 8.5 million vehicles to 26 million vehicles; in Africa (AFR), the fleet grows 190 %, from 25 million to 72 million LDVs.

3.1 EV Stock

The global stock of EVs is likewise projected to grow significantly and at a much faster rate than the global LDV stock: from about 1 million EVs in 2015 to 585–825 million EVs in 2050 depending on the scenario modeled (Figure 4). The EV total includes plug-in hybrid vehicles (PHEVs) and battery-electric vehicles (BEVs). Under our base cost assumptions, fuel cell electric vehicles (FCEV) are too expensive to enter the market without explicit support (we test a sensitivity case for hydrogen cars in Section 4). In the Reference scenario, the EV share of the global LDV fleet is projected to grow to 33 % by 2050; in the Paris Forever and Paris to 2°C scenarios, with more aggressive climate policies, the EV share grows to 38 % and 50 %, respectively.

We project that, over time, battery cost improvements and rising gasoline prices will shift the composition of the global EV fleet toward BEVs and away from PHEVs. The ratio of

FIGURE 4
Global EV stock.



BEVs to PHEVs in the global EV fleet changed from 1.4-to-1 in 2015 to 1.6-to-1 in 2017. This change was influenced by China, which is pushing BEV technology development for numerous reasons. Conversely, in the U.S. and Europe, the ratio of BEVs to PHEVs has stayed roughly the same.

Figure 5 shows our projections for the global composition of EVs in the Paris Forever scenario. While the model captures the 1.4-to-1 ratio of BEVs to PHEVs in 2015, it projects that the stock of PHEVs in the early years (up to 2025) of the study period grows at roughly the same rate as the stock of BEVs. Thereafter, BEV deployment accelerates and the ratio of BEVs to PHEVs increases over time. In 2050, the ratio is about 20-to-1 and BEVs comprise about 95 % of the global EV market. At that point, our modeling analysis projects a global stock of about 625 million BEVs and about 30 million PHEVs.

Figure 6 shows our projections for the total EV stock by region in the Paris Forever scenario. While the U.S., Europe, and China keep their leadership positions in terms of the size of

FIGURE 5
Composition of the global EV stock (numbers of BEVs vs. PHEVs) in the Paris Forever Scenario.

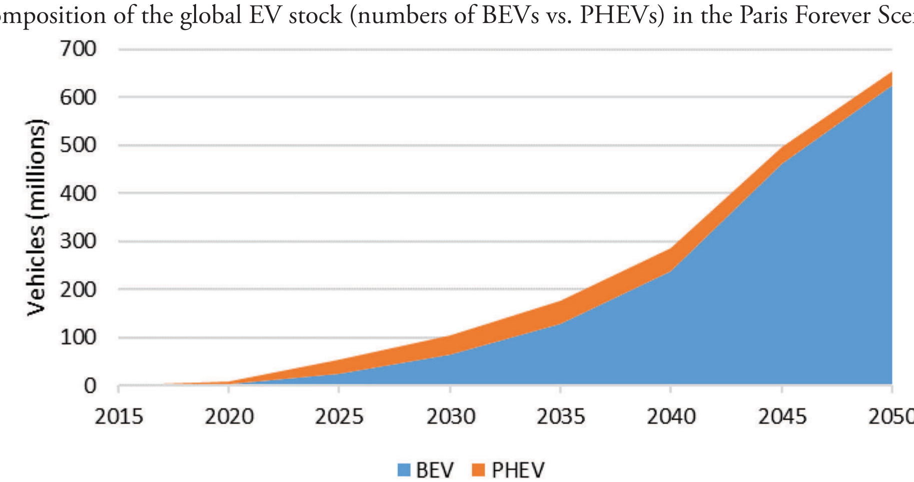
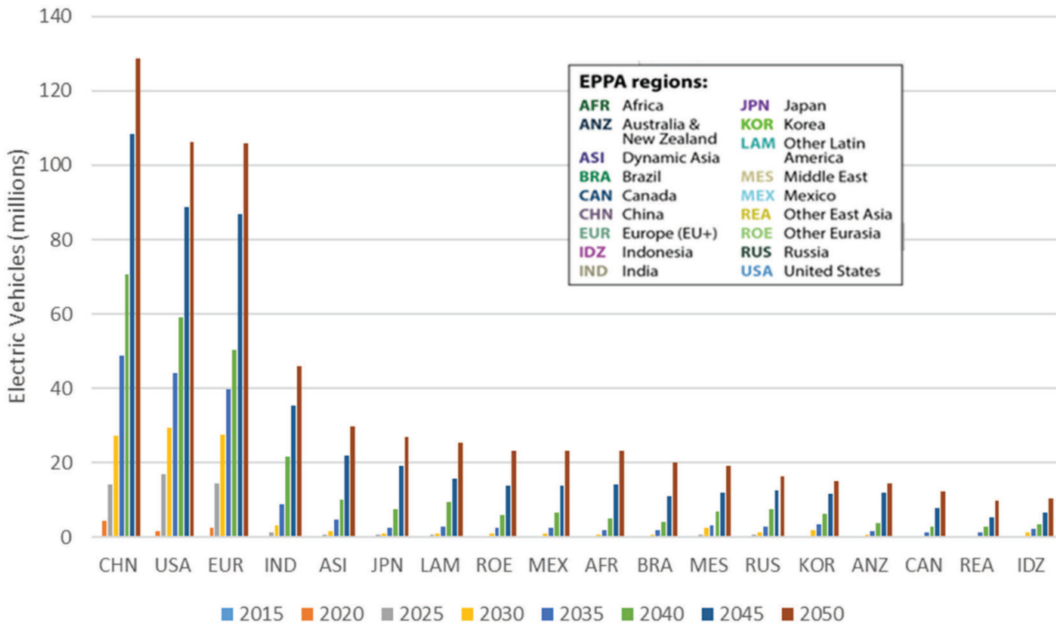


FIGURE 6
Regional LDV stock in the Paris Forever scenario.



their EV fleets (with more than 100 million EVs by 2050 in each of these regions), the number of EVs grows in all world regions. By 2050, India (IND), Brazil (BRA), Rest of Eurasia (ROE), Dynamic Asia (ASI), and Japan (JPN) have substantial EV fleets. However, the U.S., Europe, and China together still account for more than half of the global EV stock in 2050.

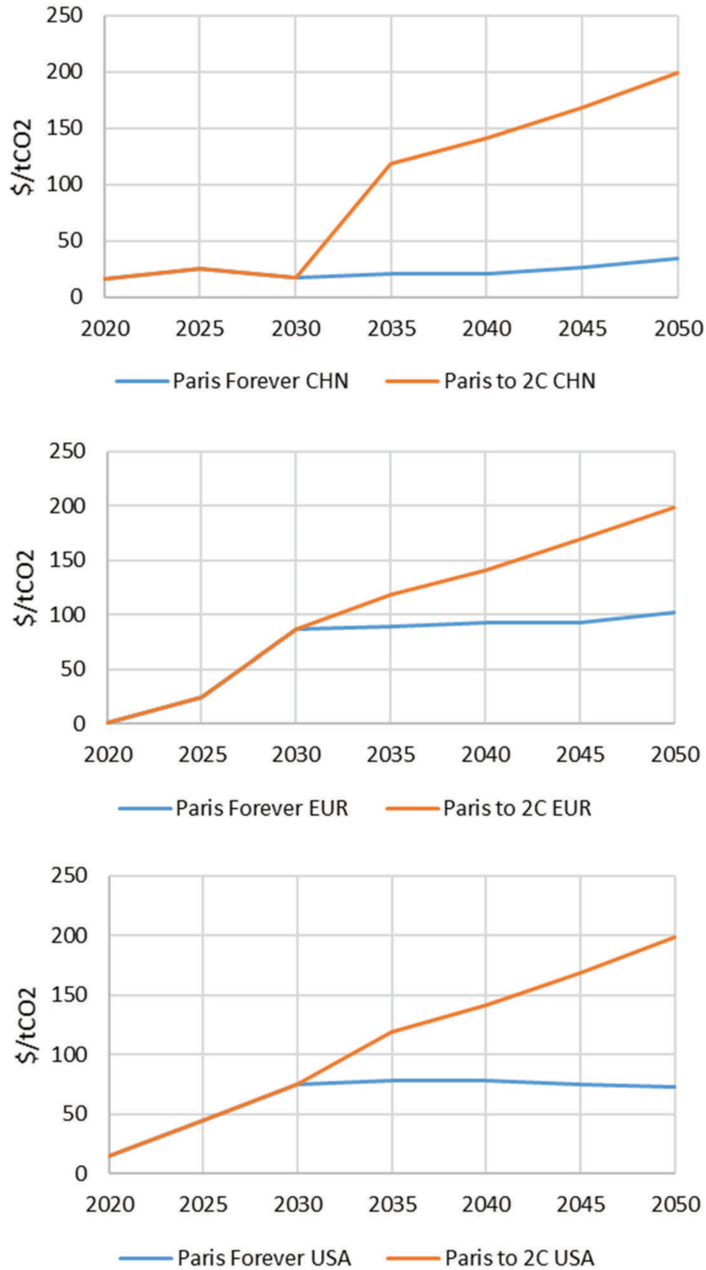
3.2 CO_2 Emissions

Projected global CO2 emissions from use of fossil fuels and from industrial processes are presented in Figure 7 in gigatonnes of carbon dioxide (Gt CO2). In the Reference scenario, global emissions grow from about 34 Gt CO2 in 2015 to about 46 Gt CO2 in 2050, a 36 % increase. In the Paris Forever scenario, global emissions are roughly stable up to 2030. After that, global emissions begin rising again due to the adoption of carbon intensity targets by China and India, which allow for continued growth in emissions with growing GDP, combined with a lack of hard emissions constraints in some less developed economies. In this scenario, global emissions grow by about 10 % from 2015 to 2050, though they are lower (by about 18 %) than they would be in the Reference scenario.

In the Paris to 2°C scenario, we assume that countries intensify their climate-change mitigation efforts after meeting their pledged "nationally determined contributions" or NDC commitments under the Paris Agreement through 2030. Specifically, we assume that countries implement the additional emissions reductions needed to achieve the overarching goal of the Paris Agreement, which is to limit the increase in global average temperature to less than 2°C. This constraint implies a sharp decline in emissions between 2030 and 2035 so as to put the world on a trajectory that is consistent with meeting the 2°C goal. While we focus on the results up to 2050, we note that stringent emission reductions are needed in the second half of the century. See Morris et al. (2021) for a discussion about the emission profiles and quantifying uncertainty in climate projections using the tool we employ in this paper.

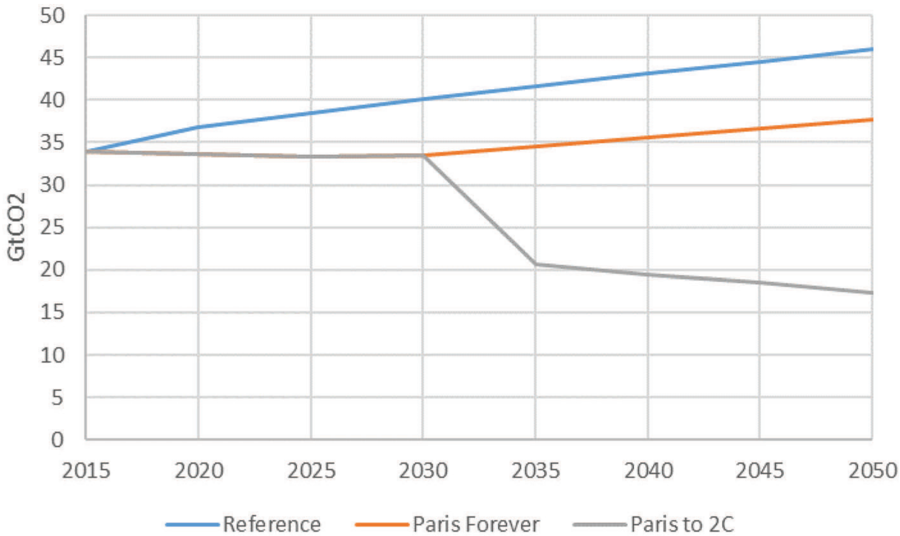
FIGURE 7

Carbon prices in the U.S., Europe, and China in different scenarios.



Our modeling for the Paris Forever scenario assumes no emissions trading, which means that each region has its own carbon price. EPPA results for projected carbon prices under this policy scenario are shown for the U.S., Europe, and China in Figure 8. The figure shows roughly stable carbon prices in these regions from 2030 to 2050 at about \$70–\$80 per tonne of CO2 (tCO2) in the U.S., \$90–\$100/tCO2 in Europe, and about \$20–\$35/tCO2 in China. All monetary values are reported in real terms in 2015 U.S. dollars.

FIGURE 8
Global CO2 emissions in different scenarios.



Our modeling for the Paris to 2°C scenario assumes that global emissions trading is introduced after 2030. In this scenario, the global carbon price increases from about \$120/tCO2 in 2035 to about \$200/tCO2 in 2050. The projected change in carbon prices between 2030 and 2035 depends on the stringency of country-level commitments under the Paris Agreement up to 2030. Regions that undertake more ambitious mitigation efforts, such as Europe and the U.S., see only a gradual increase in the carbon price as they transition from their Paris NDCs to a global carbon price that is consistent with the 2°C emissions trajectory. For China, however, the carbon price jumps dramatically, from \$17/tCO2 in 2030 to \$119/tCO2 in 2035. The model projects similarly sharp carbon price transitions in other countries that pursue less aggressive mitigation policies under the Paris Agreement. In the Paris to 2°C scenario, global CO2 emissions in 2050 are 62 % lower than in the Reference scenario and 54 % lower than in the Paris Forever scenario.

More aggressive climate policies and correspondingly higher carbon prices drive the increase in EV adoption, which in turn affects emissions from private transportation. The full emissions impact of expanded EV deployment depends on the carbon intensity of electricity production. In our Reference scenario, the global carbon intensity of electricity production starts at about 525 grams CO2 per kilowatt-hour (gCO2/kWh) in 2015 and falls to 345 gCO2/kWh by 2050. With more aggressive policies to decarbonize the electricity sector, carbon intensity falls more substantially in the two policy scenarios: to 317 gCO2/kWh in 2050 under the Paris Forever scenario, and to 95 gCO2/kWh in 2050 under the Paris to 2°C scenario. In percentage terms, the carbon intensity of electricity production is reduced by 35 %, 40 %, and 80 % between 2015 and 2050 across the three scenarios considered. This translates to an average annual rate of decline in carbon intensity of about 1.2 % per year under the Reference scenario, 1.4 % per year under the Paris Forever scenario, and 4.8 % per year under the Paris to 2°C scenario.

The speed and extent of projected electric-sector decarbonization varies across regions. China is projected to achieve carbon-intensity reductions faster than the U.S. in all scenarios. Comparing 2050 to 2015 in the Reference and Paris Forever scenarios, China reduces the carbon intensity of its electric sector by about 50 % while the U.S. achieves a 36 % reduction. In the Paris to 2°C scenario, China reduces electric-sector carbon intensity by about 97 % compared to a 50 % reduction for the U.S. Because China starts with a far more carbon-intensive power mix in 2015 (790 gCO2/kWh for China compared to 420 gCO2/kWh for the U.S.), it still ends up with a higher carbon-intensity figure for 2050 in both the Reference and Paris Forever scenarios (around 400 gCO2/kWh in China vs. around 270 gCO2/kWh in the U.S.). Under the Paris to 2°C scenario, however, China achieves lower carbon intensity than the U.S. by 2050: 26 gCO2/kWh in China versus 215 gCO2/kWh in the U.S. This is because adding zero- and low-carbon generation is cheaper in China than in the U.S. By mid-century China is projected to have a nearly carbon-free generation mix of coal with carbon capture and storage (CCS), renewables, nuclear, and hydropower. Meanwhile, the U.S. continues to use inexpensive natural gas (with and without CCS) while also expanding renewables.

3.3 Fuel Use and Prices

Projections of future consumption of liquids (oil and biofuels) and oil prices are sensitive to a host of factors, including trends in demand for personal mobility and preferred modes for delivering mobility. In 2015, LDVs accounted for almost a quarter of global oil consumption (IEA 2017). Modeling results for our *Paris Forever* scenario show a 7 % reduction in global liquids use in 2030 and an 8 % reduction in 2050 relative to the *Reference* scenario (Figure 9). The *Paris to 2°C* scenario results in a more substantial, 25 % reduction in global liquids consumption (equal to more than 60 EJ of liquid fuels) by 2050 compared to the *Reference* scenario. However, only about one-fifth of this reduction is due to the electrification of the LDV fleet. Other contributors include improved fuel efficiency (for both heavy- and light-duty vehicles), fewer vehicle miles traveled, and reduced use of oil in the industrial sector. It should be stressed that in this study we focus on LDVs. More aggressive deployment of low-carbon options in other modes of transportation would lead to larger reductions in oil use.

Policies to reduce carbon emissions will increase the price consumers pay for carbon-emitting fuels, including petroleum-based fuels, relative to the *Reference* scenario (Tables 2-3), At

FIGURE 9
Global liquids use in different scenarios.

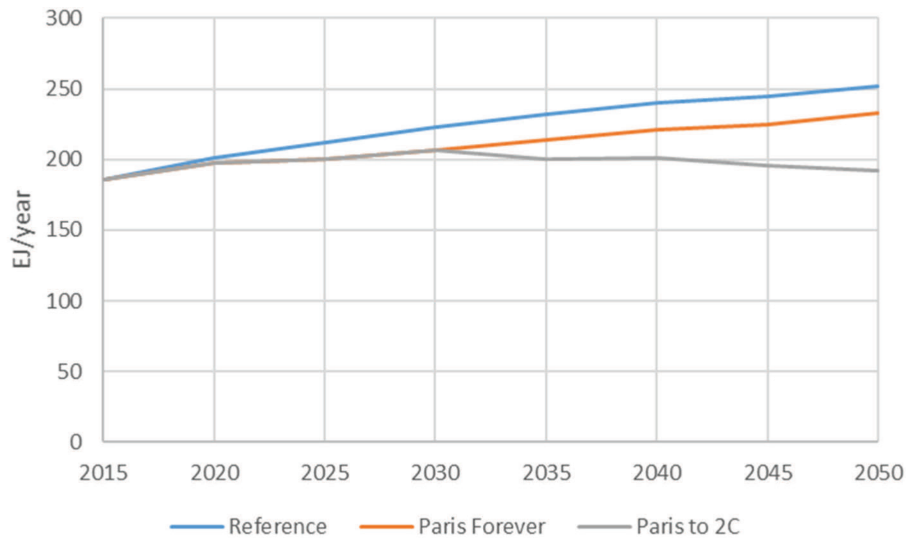
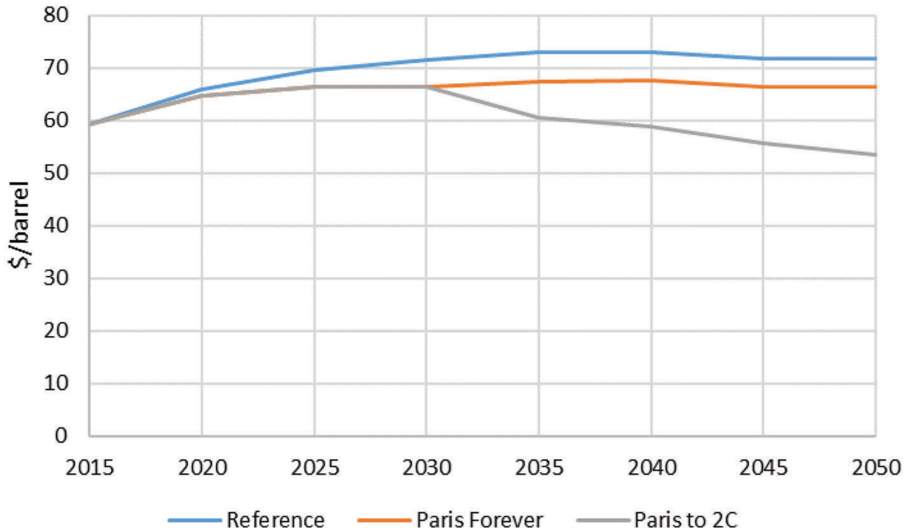


FIGURE 10
Crude oil prices to producers in different scenarios.



the same time, carbon constraints, by reducing demand for oil, reduce the prices received by oil producers. Figure 10 shows the trajectory of projected crude oil prices for producers in our modeling scenarios. In 2030, the difference between crude oil prices in the *Reference* scenario and both Paris scenarios is about $5/barrel (producers receive $71/barrel in the *Reference* scenario compared to $66/barrel in the Paris scenarios). In 2050, the price reduction to producers under carbon constraints is larger: At that point producers receive $72/barrel in the *Reference* scenario compared to $67/barrel in the *Paris Forever* scenario and $54/barrel in the *Paris to 2°C* scenario.

Crude oil is traded globally and the EPPA model treats crude oil as a homogenous product that has the same price in all regions of the world. Prices for refined oil products such as gasoline and diesel include regional taxes, tariffs, and trade margins; therefore, they differ by region. Table 2 shows projected consumer prices for gasoline in the U.S. for the three scenarios. Table 3 provides similar information for China. Policies to limit carbon emissions increase oil prices for consumers relative to the *Reference* scenario. In our analysis, carbon prices are added on top of any existing fuel taxes. In 2050, the modeled gasoline price to U.S. consumers ranges from

TABLE 2
Gasoline prices in the U.S. in different scenarios

$/gallon	Reference	Paris Forever	Paris to 2°C
2015	2.49	2.49	2.49
2020	2.72	2.86	2.86
2025	2.84	3.27	3.27
2030	2.91	3.62	3.62
2035	2.96	3.68	3.92
2040	2.96	3.70	4.10
2045	2.92	3.61	4.28
2050	2.92	3.60	4.53

TABLE 3
Gasoline prices in China in different scenarios

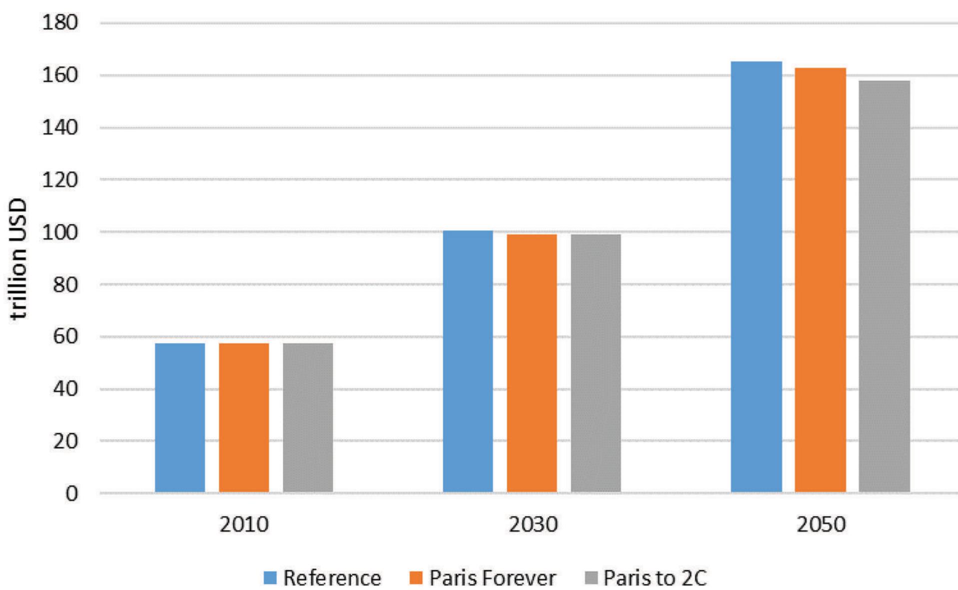
$/gallon	Reference	Paris Forever	Paris to 2°C
2015	4.52	4.52	4.52
2020	4.94	5.30	5.30
2025	5.18	5.61	5.61
2030	5.30	5.43	5.43
2035	5.39	5.56	7.03
2040	5.39	5.55	7.25
2045	5.33	5.59	7.43
2050	5.32	5.78	7.72

$2.92/gallon in the *Reference* scenario to $4.53/gallon in the *Paris to 2°C* scenario. In China the corresponding price range is from $5.32/gallon in the *Reference* scenario to $7.72/gallon in the *Paris to 2°C* scenario.

3.4 Macroeconomic Implications

Computable general equilibrium (CGE) models, like EPPA, are important tools for projecting the macroeconomic implications of different policy scenarios. We estimate that the macroeconomic costs of the modelled climate policies range from a 1.1 % to 3.3 % reduction in global GDP in 2050, relative to the *Reference* scenario. While this represents a substantial amount of money ($1–$3 trillion), the cost is equal to one-to-two years of economic growth. Figure 11 shows that the global economy is projected to expand from 2010 to 2050 in all scenarios, but economic growth under the climate policy scenarios is slower. Importantly, these calculations do not consider benefits from mitigating climate change and reducing air pollu-

FIGURE 11
Global GDP in different scenarios.



tion. Estimating such benefits is challenging, as the impacts of climate change span a large number of economic sectors and ecosystem services, are difficult to convert to monetary values, and the impacts also vary strongly by region (Monier et al. 2018). Therefore, our analysis reports only the costs of achieving emission mitigation targets.

4. SENSITIVITY ANALYSIS

Many factors might affect the pace of EV deployment and its implications for climate-related goals. To explore a wider range of future outcomes, we developed a sensitivity analysis to test the impact of different assumptions about LDV growth in China, accelerated support for EV deployment, and increased investment in renewable energy. We also examined prospects for the deployment of hydrogen cars.

4.1 Higher Demand for Private Transportation in China

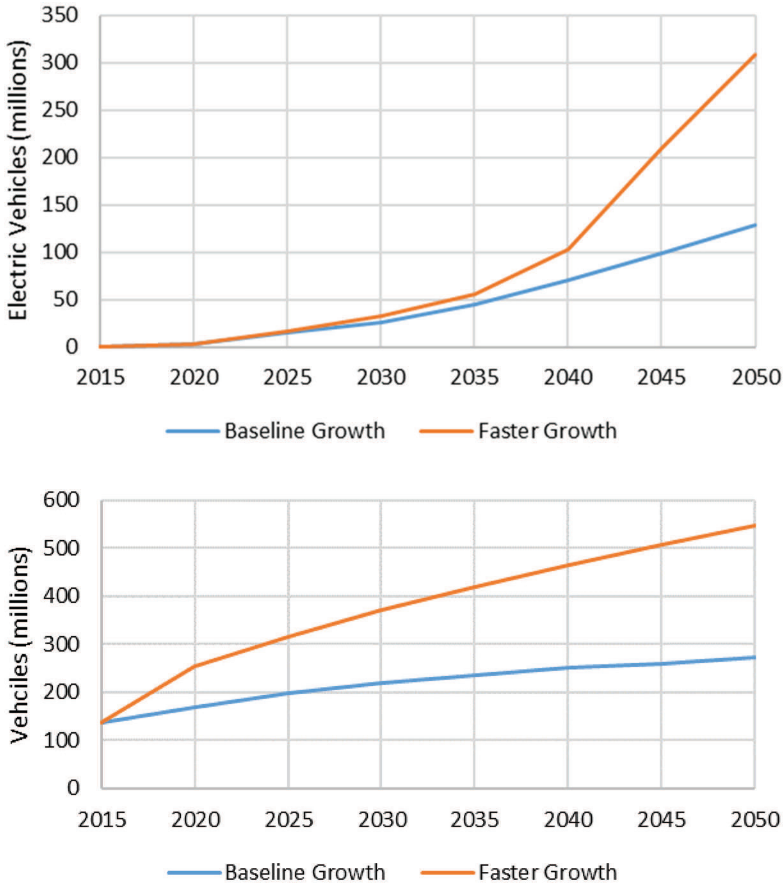
China's LDV fleet is the fastest growing in the world. Over the decade from 2005 to 2015, China's LDV fleet grew at an average rate about 10 times faster than in the rest of the world (Ghandi and Paltsev 2019). Car ownership in China is likely to continue expanding rapidly for some time, but more recently there have been some indications of slowing growth. A forecasted reduction in China's economic growth in the upcoming years (IMF 2018) together with measures to reduce congestion and local air pollution may serve to dampen LDV fleet growth. It is too early to tell if a decline in the growth of car sales in China in 2018 and 2019 is indicative of a new trend or if it is a temporary phenomenon. Here we examine how different assumptions regarding the income elasticity of demand for private transportation in China affects LDV deployment in China. Higher income elasticity means a larger increase in vehicle ownership for the same level of income growth.

As described earlier, China's LDV fleet is projected to grow to about 220 million vehicles in 2030 and 275 million vehicles in 2050 in the *Paris Forever* scenario with our baseline assumption for income elasticity. EVs constitute nearly half (47 %) of China's LDV fleet in 2050 in this scenario. Figure 12 illustrates the results when the same scenario is modeled with a higher income elasticity assumption (In the base setting we use elasticities from Kishimoto (2018). We double the elasticity in the higher income elasticity case). In this case, China's LDV stock reaches more than 370 million vehicles in 2030 and grows further, to about 550 million vehicles, in 2050. China's projected EV fleet is also larger in this case, with 33 million EVs in 2030 (versus 26 million in the baseline case) and about 308 million EVs in 2050 (versus 129 million in the baseline case). Based on these results, EVs also account for a larger share of China's overall LDV fleet in 2050: 56 % instead of 47 % in the baseline case. Nonetheless, a larger LDV fleet results in higher CO_2 emissions from China's transportation sector. In fact, under the higher income elasticity assumption, modeled transportation emissions for China more than double compared to the baseline case.

4.2 Accelerated Support for EV Deployment

As we have already noted, numerous forms of government support can lower the relative cost of owning an EV and accelerate the penetration of EVs. We tested the case where all countries increase public support for EV deployment (that results in about 15 % lower EV cost in comparison to the base case). As shown in Figure 13, the global EV fleet expands more

FIGURE 12
LDVs and EVs in China in the Paris Forever scenario.

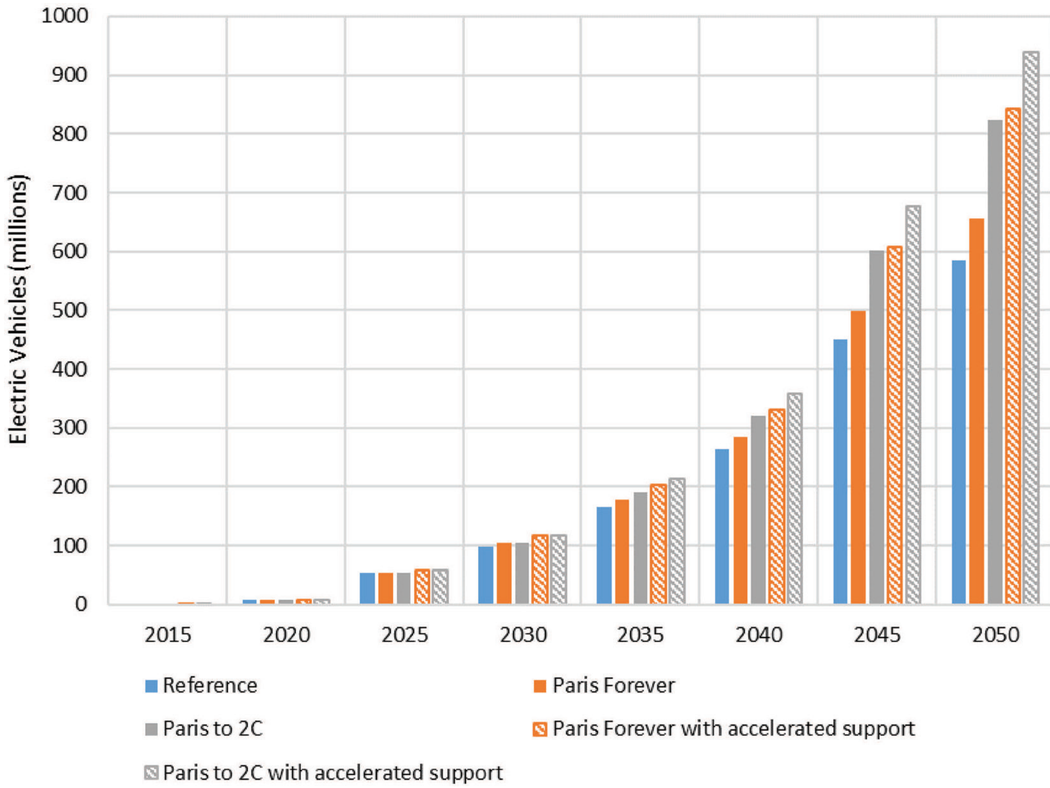


rapidly in the *Paris Forever* scenario with accelerated support, reaching about 824 million vehicles in 2050, a 28 % increase compared to the baseline support. In the *Paris to 2°C* scenario, the global EV fleet in 2050 is larger by about 15 % with accelerated support compared to the baseline setting, reaching about 940 million vehicles in 2050. Increased public support has a larger impact on projected EV fleet size under the *Paris Forever* scenario than under the more aggressive *Paris to 2°C* scenario. This is because stricter carbon constraints in the *Paris to 2°C* scenario result in higher gasoline prices, and so EVs require less support. These estimates should be treated as illustrative since they depend on the exact design of the policy mechanisms used to support EVs. While we did not explicitly model different support mechanisms, our calculations show that policies to lower the relative cost of EVs are important to accelerate EV deployment.

4.3 Accelerated Support for Renewable Electricity Generation Technologies

EV deployment will have different implications for CO2 emissions depending on the carbon intensity of the generating mix used to produce electricity for these vehicles. When powered by a generation mix that relies heavily on coal, EVs do not provide substantial CO2 benefits relative to ICEVs. As noted in our discussion of the Paris to 2°C scenario, the imposition of a uniform carbon price in all regions of the world after 2030 leads to different carbon

FIGURE 13
Global EV stock with accelerated support.



intensities of electricity production in different countries due to country-specific differences in fuel costs, technology costs, and other inputs. While the average carbon intensity of the global electricity generating mix in 2050 is 95 gCO2/kWh in the Paris to 2°C scenario, China ends up with lower carbon intensity than the U.S. (26 gCO2/kWh in China versus 215 gCO2/kWh in the U.S. in 2050). This result is driven by a global carbon price that supports a switch from coal to low-carbon generation in China, whereas natural gas in the U.S. remains competitive at that price for a long time.

To model the effect of policies that provide additional support for renewable power, we assume a lower cost for wind and solar generation relative to natural gas in all regions of the world compared to the baseline setting. The EPPA model recognizes that at low penetration of intermittent technologies in power generation, such as wind and solar, the existing dispatchable generation capacity can compensate for the intermittent power generators. At higher penetrations of intermittent power generation technologies, the EPPA baseline model represents the increased cost on the electricity power system. Intermittent renewables do not incur additional integration cost when their share in total generation is below 30%. With larger than 30% shares, intermittent power generation requires 1kW-for-1kW backup with a dispatchable technology such as gas turbines, bioelectricity, or storage (Morris et al. 2020). In the accelerated renewable electricity case in EPPA, we assume that intermittency issues are fully resolved and there is no requirement for backup for intermittent power generation technologies.

In this case, the global average carbon intensity of electricity production in 2050 drops to 25 gCO2/kWh in the Paris to 2°C scenario, while China's carbon intensity falls to 3 gCO2/

kWh and carbon intensity in the U.S. is 34 gCO2/kWh. With low-carbon power generation, EV deployment makes a larger contribution to CO2 reductions. Thus, in the U.S., accelerated support for renewable power generation produces an 83 % reduction of grid carbon intensity and a corresponding 10 % reduction in the projected carbon intensity of the overall LDV fleet in 2050.

While our results from different scenarios for the costs of integration of intermittent renewables imply that EV deployment profiles are not affected substantially by intermittency issues, economy-wide emissions and emission benefits of EVs are significantly different when the electricity sector is decarbonized. It also allows for more stringent overall emission reduction targets. These results call for combining policies that target decarbonization of transport with technology and policy solutions for including large shares of renewables in power generation.

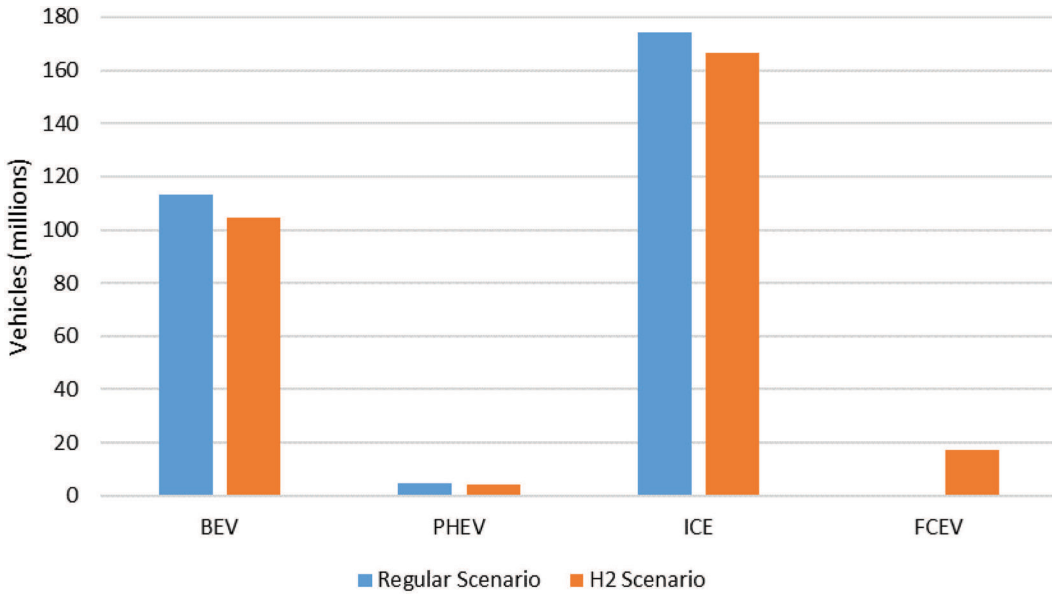
4.4 Hydrogen Cars

While EVs currently dominate the market for lower-emission vehicles, hydrogen-based vehicles offer another pathway to decarbonizing personal transportation. One option involves vehicles powered by fuel cells that generate electricity from hydrogen and oxygen. Fuel cell electric vehicles (FCEVs) are more expensive than ICEVs and they rely on infrastructure that needs substantial development. Numerous studies have examined the costs and challenges of transitioning to a hydrogen-based transportation system, including the cost of fuels, infrastructure, and vehicles (Simbeck and Chang 2002, Hydrogen Council 2017). To explore the potential role of FCEVs for purposes of our analysis, we applied several simplifying assumptions. For example, we assume that the total cost of ownership for an FCEV is twice as high as the cost of ownership for a comparable ICEV (Ghandi and Paltsev 2020) and we further assume that hydrogen would be produced in a manner that produces no CO_2 emissions (for example, through water electrolysis using zero-carbon electricity, or through steam methane reforming or biomass gasification with carbon capture). We also have not included the cost of building hydrogen production and fueling infrastructure; therefore, this scenario should be treated as an illustrative case for FCEVs.

We consider a case where FCEVs account for a mandated 5 % share of the LDV fleet in the U.S. by mid-century. This results in the addition of 17 million FCEVs but does not substantially affect the overall size of the LDV fleet in the U.S. in 2050. The total LDV fleet is about 292 million vehicles with or without the imposition of an FCEV requirement in the U.S. With this requirement, FCEVs replace about 9 million BEVs, 0.4 million PHEVs, and about 8 million ICEVs in the U.S. fleet in 2050 (Figure 14).

Introducing a 5 % FCEV mandate in the U.S. by mid-century reduces domestic oil consumption by about 0.9 %. In 2050, the projected cost of such a mandate amounts to a 0.11 % reduction in U.S. macroeconomic consumption relative to the case without a FCEV requirement. The average cost per metric ton of avoided CO_2 emissions in 2050 is also higher in the case with FCEVs: \$122/tCO_2 compared to \$105/tCO_2 without the FCEV mandate. Our illustrative calculations show that hydrogen has potential, but is currently a more expensive option for reducing LDV carbon emissions. Substantial progress toward lowering the cost of fuel cell vehicles, while also lowering the cost of hydrogen production and fueling infrastructure, is needed to realize this technology's potential.

FIGURE 14
BEVs, PHEVs, ICEVs, and FCEVs in the U.S. in the Paris to 2°C scenario in 2050.



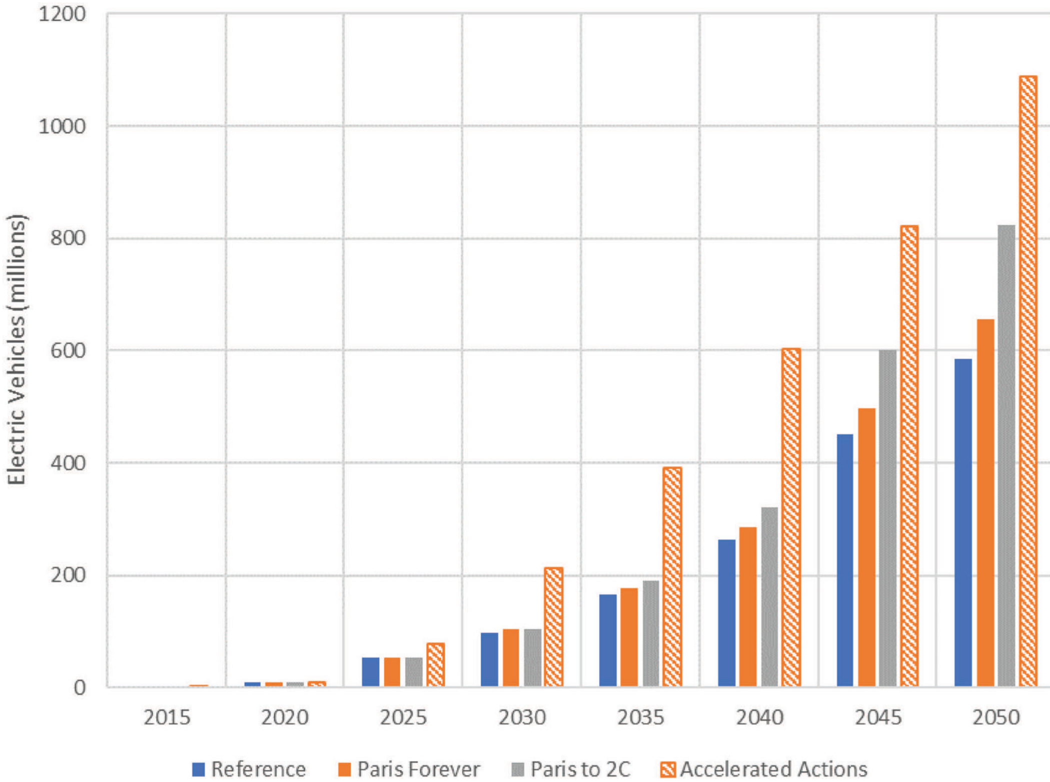
4.5 Accelerated Global Emissions Mitigation

While many countries are progressing in fulfilling their Paris pledges for 2030, even more aggressive global emission reductions are needed for reaching the long-term goal of the Paris Agreement related to "pursuing efforts to limit the temperature increase to 1.5°C" (UN 2015). To evaluate the impacts of increased ambitions, we explore an *Accelerated Actions* scenario in which countries impose much more aggressive emission targets than those submitted in their NDCs. In this scenario, we assume that advanced economies (USA, Europe, Canada, Japan, Australia and New Zealand) reduce their 2050 GHG emissions by 80% relative to their 2005 levels. Most other G20 countries reduce their 2050 GHG emissions by 50% with respect to 2005 levels (except for India and Indonesia (30%) and Russia (40%)). Africa and the Rest of East Asia end up in 2050 at their 2015 GHG levels, while other countries reduce their GHGs in 2050 by 50% relative to 2015 levels. These efforts by different countries result in global CO_2 emission reduction of about 70% in 2050 relative to 2015 levels.

While several countries have ambitious midcentury goals, many of the targets considered here do not represent actual policies in place or in planning. In addition, many developing economies call for technology transfers and financial assistance that are not forthcoming at the levels needed. We explore this scenario simply to illustrate the potential impacts of accelerated mitigation actions. In terms of climate impacts, this scenario is consistent with capping global warming at 1.5°C (Morris et al. 2021).

In this scenario, global EV stock reaches more than 200 million vehicles in 2030, 600 million in 2040, and more than one billion in 2050 (Figure 15). Assuming this accelerated deployment of EVs, two-thirds of all global LDVs by 2050 are electric. Our modeling implies that achieving a 67% electrification of the global LDV stock, global EV sales would exceed 30 million in 2030, 60 million in 2040, and 100 million in 2050. We report EV deployment by EPPA regions in Appendix E.

FIGURE 15
Impact of accelerated global mitigation actions on global EV stock.



5. CONCLUSIONS

Meeting the ambitious climate-change mitigation targets adopted by 195 nations under the Paris Agreement (UN 2015) will require substantial greenhouse gas emissions reductions across all sectors of the global economy, including personal transportation. A realistic path to decarbonizing light duty vehicle travel will require strategies that combine the task of reducing emissions with the objectives of improving personal mobility and supporting economic growth. Our modeling analysis that is designed to find the pathways that maximize welfare subject to the specific emissions, resource, and budget constraints of different countries and regions, envisions a substantial electrification of private transportation. We project that the global EV fleet will grow from approximately 5 million vehicles in 2018, to about 95–105 million EVs by 2030, and 585–823 million EVs by 2050. At this level of market penetration, EVs would constitute one-third to one-half of the overall LDV fleet by 2050 in different scenarios, with the stricter carbon constraints implied in the *Paris to 2°C* scenario leading to a larger EV share. The EV share increases with more ambitious mitigation goals. Our modeling suggests that EV uptake will vary across regions. China, the U.S., and Europe remain the largest markets in our study timeframe, but EV presence is projected to grow in all regions.

EVs play a role in reducing oil use, but a more substantial reduction in oil consumption comes from economy-wide carbon pricing. Absent more aggressive efforts to reduce carbon emissions, global oil consumption is not radically reduced in the next several decades because of increased demand from other sectors, such as for heavy-duty transport and non-fuel uses.

Our analysis indicates that global oil consumption does decline—by roughly 25 % compared to the reference case—in the *Paris to 2°C* scenario, but only about 20 % of this reduction is due to light-duty vehicle electrification.

In the *Paris to 2°C* scenario, global energy-related CO_2 emissions in 2050 are 62 % lower than in the *Reference* scenario. Although 2050 CO_2 emissions from LDVs are 43 % lower in the *Paris to 2°C* scenario than in the *Reference* scenario, this reduction in LDV emissions accounts for only 5 % of the total difference in emissions, from all sources, between the scenarios. This reflects two realities: First, as a share of global carbon emissions, LDVs are a smaller contributor (12 % of total emissions in 2015) than electricity generation (38 % of total emissions). Second, decarbonizing the electricity sector is generally less expensive than decarbonizing transportation. Since the economics of decarbonization favor greater reductions in the electricity sector, the LDV share of total carbon emissions in the *Paris to 2°C* scenario in 2050 is actually higher than the LDV share of total carbon emissions in the *Reference* scenario. The very substantial emissions reductions demanded by the *Paris to 2°C* scenario require a confluence of many factors, including electrification of about 50 % of the LDV fleet and significant decarbonization of electricity production (sufficient to achieve a 72 % reduction in the carbon intensity of the global power mix).

We estimate that the macroeconomic costs of the climate policies considered here range from a GDP loss of about 1.1 % to 3.3 % in 2050, relative to the *Reference* scenario. While these losses represent a substantial amount of money ($1–$3 trillion), they are equal in magnitude to one to two years of economic growth. Our calculations do not account for the benefits (or avoided costs) of mitigating climate change, which could also be very substantial. The global economy expands from 2015 to 2050 in all scenarios, but growth is slower in the *Paris Forever* and *Paris to 2°C* scenarios. This obviously affects overall economic activity, with implications for global oil consumption and LDV fleet size.

While we project that EVs will constitute a substantial share of the light-duty fleet by mid-century, more actions are needed to decarbonize LDV fleet. We recommend an increased ambition for climate policy actions because carbon policies will affect the speed of penetration and ultimate number of EVs on the road over the next few decades. The climate impacts of EV deployment depend on progress toward decarbonizing the electric grid. Accordingly, we recommend that policies to support EVs should go hand-in-hand with policies to support low-carbon electricity generation. Hydrogen-based FCEVs offer another pathway for decarbonization, but their potential within the mid-century timeframe depends on substantial cost reductions in terms of both vehicles and fuel production and distribution infrastructure. We recommend enhancing the support for further research and development (R&D) to advance these and other low-carbon transportation options because they will allow the attainment of more ambitious decarbonization targets. While our paper focuses on EV deployment, we also stress support for all possible decarbonization options related to transportation, including enhancing public transportation, land use planning that encourages compact areas and reducing the use of private motorized transport by mode switching to walking, biking and mass transit. Development of efficient modes of transport, like subways and high-speed rail, can offer low-emitting options for transporting people and goods.

Overall, we find that EVs, along with more efficient ICEVs, represent a viable opportunity among a set of options for reducing global carbon emissions at a manageable cost. The ultimate goal of mitigating climate change requires actions from all economic sectors, and efforts to address the contribution from personal transportation should be part of an integrated policy response to maximize human welfare, manage climate risks, and secure a foundation for sustainable economic growth and development in the future. Achieving substantial emissions reductions (and ultimately moving to zero-emissions) in the transportation sector will require not just one technology, but an integrated system approach that includes more efficient ICEVs, a long-term switch to low- and net-zero carbon fuels for transport, and increased efficiency of the transport system through digitalization, smart pricing, and multi-modal integration. Changes in consumer choices to shift from private transportation to low-emitting public transport, shared mobility, biking, and walking will also be important for creating better quality of life. Personal mobility is at the forefront of changes, and will pave the way for decarbonization in other segments of the transportation sector, such as heavy-duty vehicles and marine and air transport.

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APPENDIX A

Implementation of the Paris Agreement NDCs in modeling

Information on implementation of the Nationally Determined Contributions (NDCs) under the Paris Agreement at the country/region level of the EPPA model is provided in Table A1. Many countries describe emissions reduction targets relative to an absolute (ABS) level of emissions defined by an historical level such as 2005. Europe and Russia continue to use 1990 as the base year. Other countries such as China and India describe targets based on emissions intensity (INT).

For countries with NDCs included within larger EPPA regions, we have assessed how their targets would affect emissions for the region as a whole relative (REL) to business-as-usual (BAU), and summarize the combined effects in the next to the final column of the table as a percentage reduction of CO2-e from the identified base for each country/region, or in terms of energy intensity reductions for regions that have chosen emissions intensity as a goal. The assessment of the expected emission reduction in 2030 is based on MIT Joint Program Outlook (2018).

TABLE A1

Conversion of policies and measures into specific targets for regions of the EPPA model

Region	**NDC** Type/Base	Reduction	**CO_2-e 2005 Mt or t-CO_2/$1000**	Other Features	**Expected CO_2-e Reduction in 2030**	**Additional CO_2-e Emissions Reduction in 2050 Relative to 2030**
USA	ABS 2005	26-28% by 2025	6220		25%	30%
EUR	ABS 1990	40% by 2030	5370 (1990)	27% renewables in electricity by 2040	40%	20%
CAN	ABS 2005	30% by 2030	789	Mainly land use & forestry with 18% reduction in industrial emissions	25%	45%
JPN	ABS 2005	25% by 2030	1260	2.5% from land use change. Assumes internationally transferred mitigation outcomes	20%	40%
ANZ	ABS 2005	26-28% by 2030	596		20%	45%
BRA	ABS 2005	37% by 2025	2.19	45% of primary energy renewable by 2030; LUCF down 41% 2005-12	35%	10%
CHN	CO_2 INT 2005	60-65% by 2030	2.00 (INT)	NDC is CO_2 only, discount to account for other gases. CO_2 peak by 2030, Non-fossil 20% of primary energy	55%	60%
KOR	BAU	37% by 2030	NA	Policies and measures on renewables and autos	25%	30%
IND	INT 2005	30-36% by 2030	1.17 (INT)	2.5-3.0b tons CO_2 from forests. 40% non-fossil electric. Assumes unspecified financial assistance	30%	27%
IDZ	BAU	29% by 2030	NA	Role of LUCF (63% of current emissions). Industrial emissions increase	30%	5%
MEX	BAU	25% by 2030	NA	22% of CO2, 51% of BC, Intensity reduction of 40% 2013-2030.	25%	30%
ASI	BAU		NA	Malaysia 45% INT, Philippines 70% BAU, Thailand 20% BAU, Singapore ABS 36%	10%	45%
AFR	BAU		NA	Nigeria 45% BAU, South Africa 20-80% increase (ABS), limited information on other regions.	5%	37%
MES	BAU		NA	Saudi & Kuwait actions only, Iran 15% BAU, UAE non-GHG actions	10%	45%
LAM	BAU		NA	Argentina 15% BAU, Chile 35% INT, PERU 20% BAU, Colombia 20% BAU	10%	30%
REA	BAU		NA	Bangladesh 5% BAU, Pakistan reduction after unspecified peak, Sri Lanka 7% BAU, Myanmar & Nepal miscellaneous actions	10%	25%
ROE	BAU		NA	Azerbaijan 13% BAU, Kazakhstan 15% 1990, Turkey 21% BAU, Ukraine 40% BAU	10%	50%

APPENDIX B

Composition of the regions in the EPPA model

Country	Region
Afghanistan	REA
Albania	ROE
Algeria	AFR
American Samoa	ANZ
Andorra	ROE
Angola	AFR
Anguilla	LAM
Antigua & Barbuda	LAM
Argentina	LAM
Armenia	ROE
Aruba	LAM
Australia	ANZ
Austria	EUR
Azerbaijan	ROE
Bahamas	LAM
Bahrain	MES
Bangladesh	REA
Barbados	LAM
Belarus	ROE
Belgium	EUR
Belize	LAM
Benin	AFR
Bermuda	LAM
Bhutan	REA
Bolivia	LAM
Bosnia and Herzegovina	ROE
Botswana	AFR
Brazil	BRA
Brunei	REA
Bulgaria	EUR
Burkina Faso	AFR
Burundi	AFR
Cambodia	REA
Cameroon	AFR
Canada	CAN
Cape Verde	AFR
Cayman Islands	LAM
Central African Republic	AFR
Chad	AFR
Chile	LAM
China	CHN
Côte d'Ivoire	AFR
Colombia	LAM
Comoros	AFR
Congo	AFR
Congo, Dem. Rep. (Zaire)	AFR
Cook Islands	ANZ
Costa Rica	LAM
Croatia	ROE
Cuba	LAM
Cyprus	EUR
Czech Republic	EUR
Denmark	EUR
Djibouti	AFR
Dominica	LAM
Dominican Republic	LAM
Ecuador	LAM
Egypt	AFR
El Salvador	LAM
Equatorial Guinea	AFR
Eritrea	AFR
Estonia	EUR
Ethiopia	AFR
Falkland Islands	LAM
Faroe Islands	ROE
Fiji	ANZ
Finland	EUR
France	EUR
French Guiana	LAM
French Polynesia	ANZ
Gabon	AFR
Gambia	AFR
Georgia	ROE
Germany	EUR
Ghana	AFR
Gibraltar	ROE
Greece	EUR
Greenland	LAM
Grenada	LAM
Guadeloupe	LAM
Guam	ANZ
Guatemala	LAM
Guinea	AFR
Guinea-Bissau	AFR
Guyana	LAM
Haiti	LAM
Honduras	LAM
Hong Kong	CHN
Hungary	EUR
Iceland	EUR
India	IND
Indonesia	IDZ
Iran	MES
Iraq	MES
Ireland	EUR
Israel	MES
Italy	EUR
Jamaica	LAM
Japan	JPN
Jordan	MES
Kazakhstan	ROE
Kenya	AFR
Kiribati	ANZ
Korea	ASI
Korea, Dem. Ppl. Rep.	REA
Kuwait	MES
Kyrgyzstan	ROE
Laos	REA
Latvia	EUR
Lebanon	MES
Lesotho	AFR
Liberia	AFR
Liechtenstein	EUR
Lithuania	EUR
Luxembourg	EUR
Libya	AFR
Macau	REA
Macedonia	ROE
Madagascar	AFR
Malawi	AFR
Malaysia	ASI
Maldives	REA
Mali	AFR
Malta	EUR
Marshall Islands	ANZ
Martinique	LAM
Mauritania	AFR
Mauritius	AFR
Mayotte	AFR
Mexico	MEX
Micronesia	ANZ
Moldova	ROE
Monaco	ROE
Mongolia	REA
Montserrat	LAM
Morocco	AFR
Mozambique	AFR
Myanmar	REA
Namibia	AFR
Nauru	ANZ
Nepal	REA
Netherlands	EUR
Netherlands Antilles	LAM
New Caledonia	ANZ
New Zealand	ANZ
Nicaragua	LAM
Niger	AFR
Nigeria	AFR
Niue	ANZ
Norfolk Islands	ANZ
Northern Mariana Islands	ANZ
Norway	EUR
Oman	MES
Pakistan	REA
Palestine	MES
Panama	LAM
Papua New Guinea	ANZ
Paraguay	LAM
Peru	LAM
Philippines	ASI
Poland	EUR
Portugal	EUR
Puerto Rico	LAM
Qatar	MES
Réunion	AFR
Romania	EUR
Russian Federation	RUS
Rwanda	AFR
Saint Helena	AFR
Saint Kitts and Nevis	LAM
Saint Lucia	LAM
Saint Pierre & Miquelon	LAM
Saint Vincent & Grenadines	LAM
Samoa	ANZ
San Marino	ROE
São Tomé and Príncipe	AFR
Saudi Arabia	MES
Senegal	AFR
Serbia and Montenegro	ROE
Seychelles	AFR
Sierra Leone	AFR
Singapore	ASI
Slovakia	EUR
Slovenia	EUR
Solomon Islands	ANZ
Somalia	AFR
South African Republic	AFR
Spain	EUR
Sri Lanka	REA
Sudan	AFR
Suriname	LAM
Swaziland	AFR
Sweden	EUR
Switzerland	EUR
Syria	MES
Taiwan	ASI
Tajikistan	ROE
Tanzania	AFR
Thailand	ASI
Timor-Leste	REA
Togo	AFR
Tokelau	ANZ
Tonga	ANZ
Trinidad and Tobago	LAM
Tunisia	AFR
Turkey	ROE
Turkmenistan	ROE
Turks and Caicos Islands	LAM
Tuvalu	ANZ
Uganda	AFR
Ukraine	ROE
United Arab Emirates	MES
United Kingdom	EUR
United States	USA
Uruguay	LAM
Uzbekistan	ROE
Vanuatu	ANZ
Venezuela	LAM
Vietnam	REA
Virgin Islands, British	LAM
Virgin Islands, U.S.	LAM
Wallis and Futuna	ANZ
Yemen	MES
Zambia	AFR
Zimbabwe	AFR

APPENDIX C

Annual average GDP growth rates (%) in the Reference scenario

	2015-2019	2020-2024	2025-2029	2030-2034	2035-2039	2040-2044	2045-2049
USA	2.2	1.9	2.3	2.1	2.0	1.9	1.8
CAN	2.1	1.9	2.6	2.5	2.4	2.2	2.1
MEX	2.6	3.1	3.3	3.2	3.1	3.0	2.9
JPN	1.0	0.9	1.9	1.9	1.8	1.8	1.7
ANZ	2.8	2.7	2.7	2.6	2.5	2.4	2.3
EUR	2.1	1.7	1.8	1.8	1.7	1.7	1.6
ROE	3.9	3.6	3.3	3.2	3.2	3.0	2.9
RUS	1.2	1.6	2.5	2.2	2.1	2.0	1.9
ASI	3.8	3.8	3.2	2.5	2.5	2.4	2.5
CHN	6.5	5.5	4.4	3.7	3.5	3.2	3.0
IND	7.4	7.4	5.0	4.2	3.9	3.6	3.3
BRA	0.9	2.5	3.7	3.4	3.2	3.1	3.0
AFR	3.1	4.2	4.6	4.3	4.0	3.7	3.4
MES	2.8	3.1	3.3	3.1	2.9	2.8	2.7
LAM	1.0	2.9	3.3	3.2	3.1	3.0	2.9
REA	5.8	5.7	4.5	4.3	4.0	3.5	3.3
KOR	2.9	3.0	3.2	2.5	2.5	2.4	2.5
IDZ	5.3	5.3	3.7	3.4	3.0	2.4	2.5

APPENDIX D

Regional gasoline and electricity price indices in the Paris to 2C scenario

	Gasoline Price Index (2020=1)						
	2020	2025	2030	2035	2040	2045	2050
USA	1.00	1.14	1.26	1.37	1.43	1.50	1.58
CAN	1.00	1.10	1.24	1.25	1.29	1.32	1.36
MEX	1.00	1.06	1.06	1.28	1.32	1.36	1.42
JPN	1.00	1.02	1.05	1.08	1.10	1.10	1.12
ANZ	1.00	1.07	1.16	1.23	1.26	1.27	1.31
EUR	1.00	1.08	1.21	1.21	1.24	1.25	1.28
ROE	1.00	1.02	1.06	1.30	1.33	1.35	1.40
RUS	1.00	1.03	1.02	1.23	1.26	1.26	1.30
ASI	1.00	1.02	1.08	1.20	1.22	1.23	1.26
CHN	1.00	1.06	1.02	1.33	1.37	1.40	1.46
IND	1.00	1.02	1.02	1.17	1.19	1.19	1.21
BRA	1.00	1.06	1.07	1.15	1.20	1.25	1.31
AFR	1.00	1.02	1.03	1.27	1.30	1.32	1.36
MES	1.00	1.02	1.11	1.26	1.29	1.31	1.34
LAM	1.00	1.03	1.05	1.24	1.27	1.29	1.33
REA	1.00	1.02	1.03	1.22	1.24	1.25	1.28
KOR	1.00	1.05	1.10	1.13	1.14	1.14	1.16
IDZ	1.00	1.10	1.12	1.19	1.24	1.25	1.28

Electricity Price Index (2020=1)							
	2020	2025	2030	2035	2040	2045	2050
USA	1.00	1.15	1.28	1.47	1.55	1.61	1.66
CAN	1.00	1.09	1.19	1.37	1.45	1.52	1.57
MEX	1.00	1.03	1.03	1.09	1.05	1.05	1.06
JPN	1.00	1.05	1.09	1.18	1.22	1.17	1.16
ANZ	1.00	1.11	1.26	1.46	1.50	1.54	1.58
EUR	1.00	1.11	1.22	1.25	1.28	1.28	1.27
ROE	1.00	1.01	1.04	1.24	1.28	1.32	1.29
RUS	1.00	1.06	1.06	1.44	1.47	1.42	1.49
ASI	1.00	1.03	1.21	1.48	1.56	1.59	1.49
CHN	1.00	1.11	1.07	1.43	1.30	1.27	1.25
IND	1.00	1.10	1.26	1.65	1.67	1.75	1.82
BRA	1.00	1.16	1.28	1.53	1.42	1.48	1.45
AFR	1.00	1.08	1.15	1.48	1.52	1.53	1.57
MES	1.00	1.01	1.07	1.17	1.04	0.97	0.96
LAM	1.00	1.04	1.08	1.36	1.42	1.47	1.52
REA	1.00	0.97	0.94	1.05	1.07	0.99	0.92
KOR	1.00	1.12	1.29	1.41	1.40	1.37	1.36
IDZ	1.00	0.98	0.98	1.01	1.05	1.05	1.05

APPENDIX E

EV stock in different scenarios

Stock of Electric Vehicles (PHEV+BEV) in Paris Forever scenario (millions)								
	2015	2020	2025	2030	2035	2040	2045	2050
EUR	0.3	2.5	14.5	27.7	39.7	50.4	86.8	105.8
USA	0.4	1.8	17.0	29.6	44.1	59.0	88.8	106.2
CHN	0.3	4.5	14.3	27.3	48.7	70.7	108.5	128.6
IND	0.0	0.0	1.3	3.1	8.9	21.6	35.4	46.1
LAM	0.0	0.2	0.6	1.2	3.1	9.6	15.8	25.5
MES	0.0	0.1	0.9	2.5	3.3	7.1	12.1	19.1
AFR	0.0	0.1	0.3	0.6	1.9	5.1	14.3	23.1
ASI	0.0	0.2	0.9	1.7	4.7	10.2	21.9	29.7
JPN	0.1	0.3	0.7	1.2	2.6	7.6	19.3	27.1
ROE	0.0	0.1	0.5	0.9	2.6	6.0	14.0	23.2
MEX	0.0	0.0	0.6	1.1	2.7	6.8	13.8	23.2
RUS	0.0	0.1	0.8	1.3	3.1	7.6	12.7	16.4
BRA	0.0	0.1	0.5	0.9	2.0	4.0	11.1	20.0
CAN	0.0	0.1	0.3	0.5	1.4	2.9	8.0	12.2
IDZ	0.0	0.1	0.6	1.3	2.4	3.5	6.7	10.4
KOR	0.0	0.1	0.5	2.1	3.5	6.2	11.6	15.0
ANZ	0.0	0.1	0.4	0.7	1.7	4.0	11.9	14.4
REA	0.0	0.0	0.3	0.6	1.3	3.1	5.3	9.7
World	*1*	*11*	*55*	*104*	*178*	*285*	*498*	*656*

Stock of Electric Vehicles (PHEV+BEV) in Paris to 2C scenario (millions)								
	2015	2020	2025	2030	2035	2040	2045	2050
EUR	0.3	2.5	14.5	27.7	43.5	60.4	118.5	147.4
USA	0.4	1.8	17.0	29.6	44.5	60.7	108.9	135.1
CHN	0.3	4.5	14.3	27.3	53.2	85.6	140.9	174.7
IND	0.0	0.0	1.3	3.1	10.0	23.4	42.1	57.7
LAM	0.0	0.2	0.6	1.2	3.8	9.7	16.3	26.2
MES	0.0	0.1	0.9	2.5	3.3	7.3	12.3	22.0
AFR	0.0	0.1	0.3	0.6	2.1	5.5	15.6	29.2
ASI	0.0	0.2	0.9	1.7	4.7	10.8	22.2	35.7
JPN	0.1	0.3	0.7	1.2	3.7	9.9	22.0	35.0
ROE	0.0	0.1	0.5	0.9	2.7	6.2	14.2	24.0
MEX	0.0	0.0	0.6	1.1	3.2	7.7	15.1	25.9
RUS	0.0	0.1	0.8	1.3	3.3	8.1	12.8	20.5
BRA	0.0	0.1	0.5	0.9	2.1	4.1	12.0	21.2
CAN	0.0	0.1	0.3	0.5	1.4	2.9	8.3	13.5
IDZ	0.0	0.1	0.6	1.3	2.5	3.5	7.5	10.9
KOR	0.0	0.1	0.5	2.1	3.8	6.8	13.4	17.4
ANZ	0.0	0.1	0.4	0.7	1.8	4.3	13.7	17.0
REA	0.0	0.0	0.3	0.6	1.5	3.8	5.9	9.9
World	*1*	*11*	*55*	*104*	*191*	*321*	*602*	*823*

Stock of Electric Vehicles (PHEV+BEV) in Accelerated Actions scenario (millions)								
	2015	2020	2025	2030	2035	2040	2045	2050
EUR	0.3	2.5	22.6	55.9	93.9	131.9	164.2	203.4
USA	0.4	1.8	20.1	48.6	80.6	113.4	145.4	183.0
CHN	0.3	4.5	16.9	50.3	91.9	142.2	193.1	250.3
IND	0.0	0.0	1.1	4.9	11.7	22.1	34.0	50.8
LAM	0.0	0.2	1.0	3.8	9.2	16.7	25.7	37.9
MES	0.0	0.1	0.9	3.6	8.5	15.4	23.6	34.5
AFR	0.0	0.1	0.8	3.3	8.1	15.6	25.2	38.8
ASI	0.0	0.2	1.0	4.2	9.8	17.5	26.4	38.4
JPN	0.1	0.3	4.0	9.4	15.4	21.3	26.8	32.3
ROE	0.0	0.1	1.0	4.0	9.2	16.5	25.0	36.6
MEX	0.0	0.0	0.8	3.2	7.4	13.2	20.1	29.3
RUS	0.0	0.1	1.0	3.8	8.4	14.1	20.0	27.5
BRA	0.0	0.1	0.8	3.4	7.7	13.6	20.5	29.5
CAN	0.0	0.1	1.7	4.6	9.5	15.7	22.3	30.1
IDZ	0.0	0.1	0.5	1.9	4.4	7.8	11.3	16.0
KOR	0.0	0.1	1.4	3.9	6.9	10.4	14.2	18.7
ANZ	0.0	0.1	1.4	3.8	6.7	10.3	14.0	18.3
REA	0.0	0.0	0.3	1.2	3.0	5.6	8.7	12.8
World	*1*	*11*	*77*	*214*	*392*	*603*	*821*	*1,088*

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