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Global climate change mitigation potential from a transition to electric vehicles

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Summary

Through 2015, many governments have announced new climate change mitigation commitments that include national or regional commitments to reduce their carbon emissions in the 2025-2035 timeframe. The high-level government commitments to the United National Framework Convention on Climate Change Conference of the Parties process tend not to have detailed sector-specific, technology-specific commitments. However, the underlying government planning efforts and national actions do tend to be linked with a major transformation in the transport sector toward advanced efficiency technology with a shift to lower-carbon energy sources.

This paper investigates the potential for electric vehicles to contribute toward leading nations' climate goals. The analysis is specifically designed to quantify the upper bound climate benefits from the most proactive governments meeting their long-term goals to decarbonize passenger vehicles with increased penetration of plug-in electric and hydrogen fuel cell technology. The analysis includes a cataloguing of existing national electric vehicle targets and consideration for plausible market growth for the new technology. In addition, the analysis includes a synthesis of data on future overall vehicle sales, vehicle activity, vehicle efficiency, and grid carbon emissions through 2050, with emphasis on the currently leading electric vehicle markets of China, Europe, and the United States. The analysis is focused exclusively on technology changes from increasing efficiency and increased uptake of electric vehicles in the light-duty vehicle fleet.

Figure S-1 summarizes greenhouse gas emission reduction for a scenario that builds from near-term government goals toward extensive deployment of electric vehicles powered increasingly by low-carbon energy sources through 2050. As indicated from this analysis, in the earlier years, electric vehicle benefits are limited by electric vehicle sales growth and fleet turnover, but the climate benefits increase greatly over time. The potential emission reductions in 2030 are 125 million metric tons CO_2, with the vast majority of those impacts being in leading electric vehicle markets of China, Europe, and the United States. As shown, the potential long-term carbon emissions benefits from electric vehicles are more dramatic at about 1.5 billion metric tons CO_2 per year in 2050, with the benefits more globally distributed by 2050.

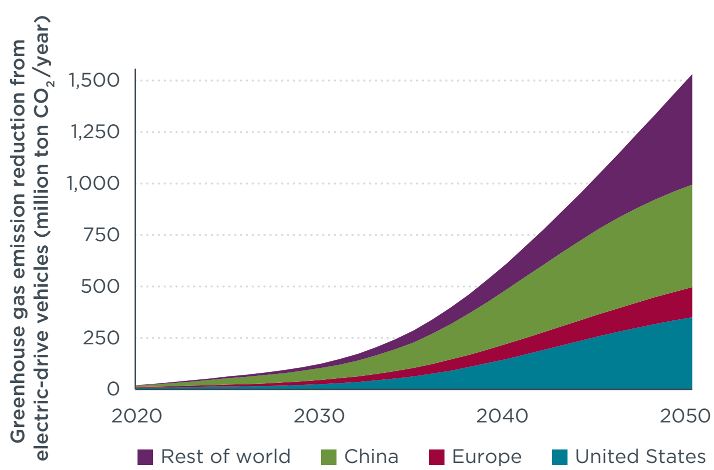

Figure S-1. Global greenhouse gas emission reduction from increased penetration of electric vehicles through 2050

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Based on this paper's findings, we draw two main conclusions:

> ***Governments' electric vehicle targets amount to more than 30 million cumulative electric vehicles by 2025.*** In 2014, the share of new vehicles that are plug-in electric vehicles is about 0.5%—2% in most major vehicle markets, although a number of particular markets are showing substantially greater penetration. Allowing for near-term supply constraints, electric vehicle sales share could increase to at least 10%—15% across leading markets around 2025. This would amount to a massive deployment of electric vehicles and will require improvements in the electric vehicle supply chain, far greater auto manufacturing scale, lower cost next-generation electric vehicle models, and sustained regulation and support from governments.
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> ***Electric vehicles' potential climate benefits could increase dramatically over time, from over 125 million tons CO_2 per year in 2030 to over 1.5 billion tons CO_2 per year in 2050***. The carbon mitigation would result from more electric vehicles entering the fleet while lower-carbon energy sources become widely available. Electric vehicle technology allows the global fleet to achieve approximately 40% lower carbon emissions than a highly efficient conventional combustion fleet (and 70% lower carbon than a business-as-usual fleet) in 2050. Matching the earlier projected electric vehicle deployment, electric vehicle climate benefits will initially be highest in European nations and in select United States regions. Over the long-term, potential electric vehicle climate benefits are greatest in China and other emerging automobile markets.

This analysis points toward future research, as well as broader implications for global electric vehicle collaboration. First, continued research into the underlying factors of this analysis could help assess the sensitivity of the results to various vehicle technology, lifecycle emission, travel activity, and policy assumptions across global markets. Second, there are questions related to achieving the required global scale to move toward an increasingly electric-drive fleet and the associated policy involved. This work indicates that leading climate mitigation policymakers could include electric vehicles as a core component of their local, state, national, and multi-government climate commitments. Establishing a global target to move toward all zero-emission passenger vehicles over the 2025 to 2050 time frame would provide a common vision and set clear signals for the pace of technology development and the amount of resources that will be needed. Multi-government collaboration on early lessons, emerging best practices, and policy effectiveness would help prioritize government actions to further increase zero-emission vehicle uptake and use.

I. Introduction

Through 2015, many governments have announced new climate change mitigation commitments that include national or regional commitments to reduce their carbon emissions in the 2025-2035 timeframe. The high-level government commitments to the United National Framework Convention on Climate Change Conference of the Parties process tend not to have detailed sector-specific, technology-specific commitments. However, the underlying government planning efforts and national actions do tend to be linked with a major transformation in the transport sector toward advanced efficiency technology with a shift to lower-carbon energy sources.

It is becoming increasingly clear that to achieve climate change stabilization goals, a large-scale shift from the internal combustion of petroleum fuels to electric-drive vehicles powered by low-carbon energy sources will be necessary. In 2015, the early growth stages of the electric vehicle industry are underway. Electric vehicles are being offered and sold in much greater numbers around the world than just several years before. In 2010, there were just hundreds of sales of new plug-in electric vehicles by major automakers. In 2014, the total global electric vehicle sales were approximately 300,000. In September 2015, the cumulative global sales of plug-in electric vehicles surpassed one million (Lutsey, 2015a).

The growth in electric vehicle sales has been disproportionately in a handful of markets where governments and automobile manufacturing companies have put increased emphasis. Figure 1 provides a summary of light-duty electric vehicle sales by major market in 2014, including sales in the leading national electric vehicle markets. As depicted, the vast majority of electric vehicle sales are in ten markets, primarily in the United States, China, Japan, and several European nations. The ten countries shown in the figure represent 92% of electric vehicle sales.

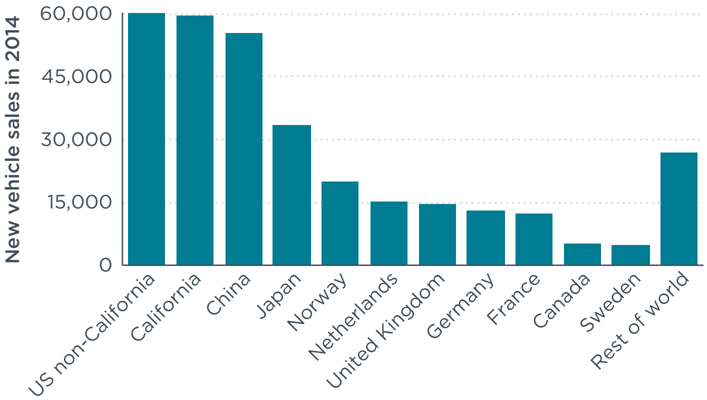

Figure 1. Electric vehicle sales and cumulative percent of global electric vehicle sales in 2014 in leading markets

Government policy is a strong driver of early growth in the electric vehicle market. These leading electric vehicle markets tend to have greater electric vehicle incentives (e.g., see Mock and Yang, 2014; OECD, 2015). The electric vehicle market growth is quite closely tied not only to federal incentives, but also regional and local actions including regulatory policy, financial and non-financial incentives, infrastructure support, and consumer awareness activities (see Lutsey, 2015a, 2015b; Lutsey et al., 2015). China, France, Germany, Japan, the Netherlands, Norway, the United Kingdom, and the United States in particular dominated global electric vehicle sales with over 90% of the 300,000 sold in 2014. Each of these markets has between 9 and 13 major electric vehicle promotion actions in place, including vehicle manufacturer-focused policies, consumer purchase policies, consumer vehicle use policies, electric charging infrastructure support, and consumer awareness activities to help break down the prevailing market barriers.

This paper investigates the potential for electric vehicles to contribute toward leading nations' climate goals. This analysis evaluates the associated carbon emissions impacts from achieving the relatively near-term government electric-drive goals for 2020-2025 and long-term government goals for all or nearly all electric-drive vehicles in the approximate 2040-2050 timeframe. Throughout this paper electric vehicles or "zero-emission vehicles" include battery electric, plug-in hybrid electric, and hydrogen fuel cell vehicles. The analysis is specifically designed to quantify the upper-bound climate benefits from the most proactive governments meeting their long-term goals to decarbonize passenger vehicles with increased penetration of electric vehicles and ultra-low-carbon electricity generation and hydrogen production.

The analysis includes a cataloguing of existing national electric vehicle targets and consideration for plausible market growth for the new technology. In addition, the analysis includes a synthesis of projections on future vehicle sales, vehicle activity, vehicle efficiency, and electric grid and hydrogen carbon emissions, with emphasis on the currently leading electric vehicle markets of China, Europe, and the United States. The analysis is focused exclusively on technology changes in light-duty vehicles and the energy sources that fuel or power them. The differences in the various technologies' projected vehicle manufacturing emissions are not included in the analysis.

Following this introduction section, Section II analyzes governments' electric vehicle targets, the research literature on long-term electric vehicle deployment, and the carbon mitigation potential for electric-drive vehicles. Section III presents results for region-specific greenhouse gas emission reduction potential through 2050. Finally, Section IV provides a summary discussion relating the potential contribution of electric vehicles to transportation climate change mitigation goals.

II. Analysis of electric vehicle climate benefits

This section provides a summary of electric vehicle targets by governments around the world, estimates a long-term scenario for electric vehicle market success based on international government goals, and quantifies the associated electric grid and hydrogen greenhouse gas emissions.

NEAR-TERM ELECTRIC VEHICLE TARGETS

Many governments have made announcements and set goals to promote the deployment of electric vehicles in the 2020 to 2030 timeframe. As a result of their analytical and planning efforts, they have publicized targets, goals, roadmaps, strategic plans, and ambitions for the rollout of electric vehicles. Table 1 summarizes electric vehicle goals that have been made by governments. Generally national governments have set and announced these goals in terms of cumulative sales, registered vehicles, or total stock targets (e.g., 1 million vehicles by a given date). Generally, the data reporting of progress toward the cumulative goals is collected as the total number of registered vehicles. Comparatively, cumulative global electric vehicle sales surpassed 700,000 at the end of 2014, and one million in September 2015. Together these goals, if simply summed, amount to at least 15 million electric vehicles globally by 2020, and over 25 million vehicles in the 2025-2030 timeframe. The context and details of each goal vary greatly, so the initial source for each target is provided. The

Table 1. Selection of national electric vehicle sales goals for 2020-2030

Region	Electric vehicle goal	
Canada (Ontario only)	1 in 20 (5%) vehicle stock (2020)	Ontario, 2009
Canada (Québec only)	100,000 cumulative sales (2020) 300,000 cumulative sales (2026)	Québec, 2015
China	1 million annual sales (2020) 3 million annual sales (2025)	MIIT, 2015
Denmark	200,000 cumulative sales (2020)	IEA, 2012
France	1-2 million cumulative sales (2020)	ADEME, 2010
Germany	1 million cumulative sales (2020) 6 million cumulative sales (2030)	BMUB, 2014
India	320,000 cumulative sales (2020)	SIAM, 2011
Japan	15-20% annual vehicle sales (2020) 20-30% annual vehicle sales (2030)	METI, 2010
Netherlands	200,000 cumulative sales (2020) 1 million cumulative sales (2025)	IEA, 2015
Norway	50,000 cumulative sales (2018)	AVERE, 2012
South Korea	200,000 cumulative sales (2020)	Han, 2015
Spain	250,000 cumulative sales (2014)	IEA, 2012
Sweden	600,000 cumulative sales (2020)	IEA, 2012
United Kingdom	5% annual vehicle sales (2020)	OLEV, 2013
United States	1 million cumulative sales (2015)	US DOE, 2011
United States (Eight states) [a]	3.3 million cumulative sales (2025)	NESCAUM, 2014
United States (California only)	0.5 million cumulative sales (2020) 1.5 million cumulative sales (2025)	California, 2013

[a] California, Massachusetts, Connecticut, Oregon, Maryland, Rhode Island, New York and Vermont

electric vehicle targets are shown in the original form that they have been stated — ranging from sales, to cumulative or stock number, to percent sales share, to percent vehicle stock for electric vehicles.

The various governments' electric vehicle targets have differing applicability by technology. While several of the targets include hybrid and plug-in electric vehicles, many others predominantly refer to plug-in electric vehicles. Often fuel cell electric vehicle targets are included in government dialogue and analytical scenarios about future electric vehicle deployment, but no countries have specific hydrogen fuel cell electric vehicle targets. Although plug-in electric automobiles make up the vast majority of the electric vehicle market today, the longer-term scope of this paper on passenger electric vehicles includes both plug-in electric and hydrogen fuel cell vehicle technology for the 2025-and-beyond projections.

Many governments have announced that their original goals will not be met for a variety of reasons, and some have recently modified their older goals. For example, Spain's original target of 250,000 electric vehicles by 2014 has not been achieved. In another example, cumulative electric vehicle sales in the United States through 2014 were less than 300,000, compared to the country's goal for 1 million vehicles by 2015. Similarly, China is not on track for its original goal for 500,000 cumulative electric vehicle sales through 2015, and it has recently announced new goals for 2020 and 2025. The original goals sum up to an increase to approximately 5.5 million annual electric vehicle sales in 2020 and about 15 million cumulative electric vehicle sales through 2020 (as summarized previously by CEM, 2015, but excluding hybrids). In order to meet these targets, electric vehicle sales would have to grow by over 60% per year through 2020.

For this assessment of international governments' electric vehicle goals, the timelines are extended to adjust for the current market situation. In addition, several modifications are made to acknowledge constraints and barriers in the growth of the early electric vehicle market within the next several years. Prevailing barriers include supply chain development for electric-drive components, cost of electric vehicle technology, varying electric vehicle model availability across markets, acceptance by a more widespread consumer base, and electric vehicle charging infrastructure. Each market has, through first-generation electric vehicle model launches and early policy action, continued to learn from its experience. In addition, leading companies and suppliers continue to innovate, reduce costs, and adapt to meet consumer demands. As a result, electric vehicle deployment goals are still tenable, just not in all cases on the original timelines.

In this assessment, modifications to the various governments' targets are made to acknowledge the slower-than-expected early growth of the market as follows. First, the initial starting point for each market is the actual 2014 electric vehicle sales share, which is less than a 1% share of new vehicles in most of the markets. Second, compounded annual global growth of the market for 2015-2020 is constrained to less than 50% per year to acknowledge that all markets cannot have unconstrained growth when the global market is dependent upon the 10-15 major automobile companies that are selling electric vehicles in the tens of thousands of vehicle per year in 2014. This leads to a projected increase from 300,000 electric vehicle sales in 2014 to approximately 3 million global electric vehicle sales in 2020. Third, electric vehicle growth was made approximately consistent among countries to acknowledge how particular markets are unlikely to get such disproportionate percentages of electric vehicle sales as the global market grows larger in volume.

Table 2 summarizes the modifications made to the existing electric vehicle targets in this assessment. The approximate impact of these changes is to shift the timeframe of existing targets that were the most ambitious back by several years, and to retain the timelines for those government goals that could be met with more plausible growth rates. One key assumption as mentioned above is that the compounded global growth rate for 2015-2020 is projected to be below 50%. The growth rates for each market decrease over time, such that the electric vehicle sales growth rates in the 2020-2025 period average

Table 2. Modifications to national electric vehicle sales goals for 2020-2030

Region	Electric vehicle goal	
Canada (Ontario only)	1 in 20 (5%) vehicles stock (2020)	Modified 5% vehicle stock goal for 2020 to 5% sales share goal in 2020
Canada (Québec only)	100,000 cumulative sales (2020) 300,000 cumulative sales (2026)	Assume goals are achieved
China	1 million annual sales (2020) 3 million annual sales (2025)	Assume goals are achieved
Denmark	200,000 cumulative sales (2020)	Goal timeline shifted from 2020 to 2025
France	1-2 million cumulative sales (2020)	Goal timeline shifted from 2020 to 2025
Germany	1 million cumulative sales (2020) 6 million cumulative sales (2030)	2020 goal shifted to 2021 (2030 retained)
India	320,000 cumulative sales (2020)	Assume goal is achieved, growth continues to 2025
Japan	15-20% annual vehicle sales (2020) 20-30% annual vehicle sales (2030)	Interim 2020 goal of 17.5% shifted to 2023; Assume 25% share achieved in 2025
Netherlands	200,000 cumulative sales (2020) 1 million cumulative sales (2025)	Assume goals are approximately achieved with continued growth
Norway	50,000 cumulative sales (2018)	Already met 2018 goal in 2015, assume continued growth
South Korea	200,000 cumulative sales (2020)	Assume goal is achieved, growth continues to 2025
Spain	250,000 cumulative sales (2014)	Goal timeline shifted from 2014 to 2022, growth continues to 2025
Sweden	600,000 cumulative sales (2020)	Goal timeline shifted from 2020 to 2028
United Kingdom	5% annual vehicle sales (2020)	Assume goal is achieved, growth continues to 2025
United States	1 million cumulative sales (2015)	Goal timeline shifted from 2015 to 2018
United States (Eight states)[a]	3.3 million cumulative sales (2025)	Assume goal is achieved
United States (California only)	0.5 million cumulative sales (2020) 1.5 million cumulative sales (2025)	Assume goals is achieved

[a] *California, Massachusetts, Connecticut, Oregon, Maryland, Rhode Island, New York and Vermont*

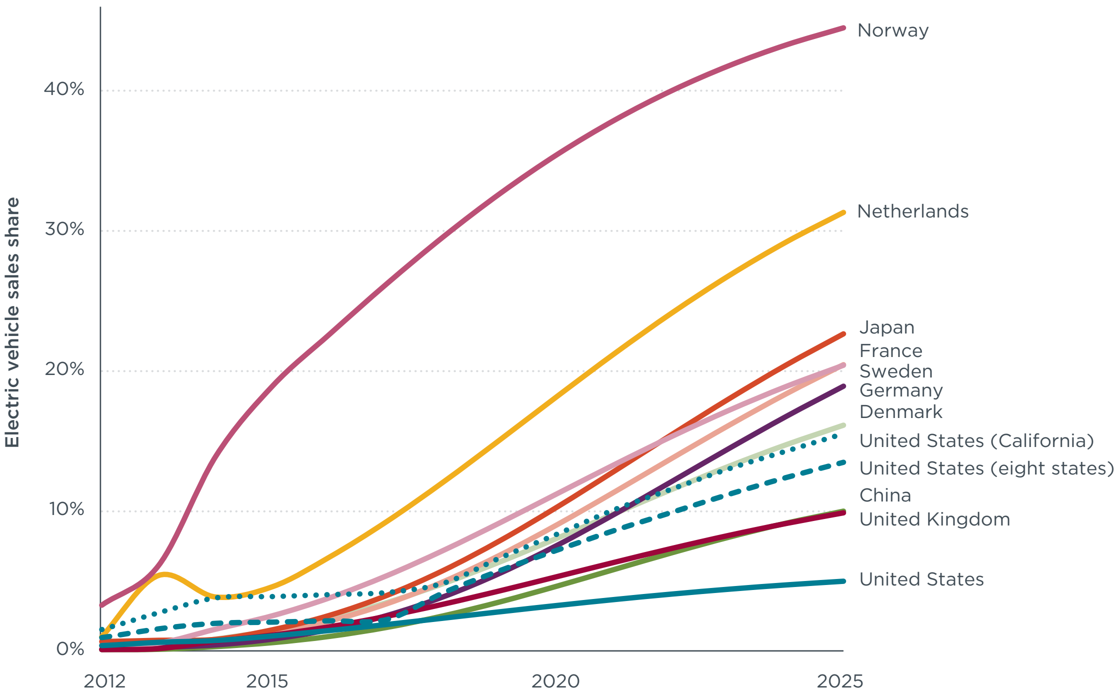

Figure 2. Share of new vehicle sales that are electric vehicles

about 19% for countries with targets. Acknowledging the importance of the various technology types of zero-emission vehicles, these targets include all plug-in electric vehicles (i.e., plug-in hybrids and all-electric vehicles) as well as fuel cell electric vehicles. It is emphasized that, even with declining electric vehicle growth rates, near-term trajectories represent a very rapid growth rate that will require many supportive technological advancements and policy actions.

In addition to the above constraints on electric vehicle market growth, as a further approximate check on the pace of market development, the electric vehicle growth rates analyzed here are compared against the leading markets' sales shares. Norway and the Netherlands have provided early evidence of how quickly early electric vehicle markets can grow with 6-14% and 4-6% of new vehicle sales, respectively, in 2013-2014. These two markets give an indication of the extent to which incentives that largely negate any electric vehicle price premium, and also provide perks to overcome various market barriers, can accomplish in growing the early market. In addition, California's extensive Zero Emission Vehicle program with regulatory requirements for vehicle manufacturers — coupled with incentives, infrastructure support, and consumer outreach — is an example of an approach that could result in at least 15% electric vehicle share by 2025.

Figure 2 illustrates the shares of new vehicles that are zero-emission vehicles based on government goals, modified as described above, through 2025. As shown, the zero-emission vehicle goals, once modified for plausible constraints, generally result in a 10-20% share of new vehicles being electric drive in the 2025 timeframe. There are several outliers shown in the chart: Norway and the Netherlands are shown to have higher zero-emission shares while India, the United States, and China have lower zero-emission vehicle shares through 2025. These zero-emission vehicle shares are based on several assumptions about the growth of the overall vehicle fleet. In order to project shares based on the future growth of the vehicle fleet, 2014 and future year sales data are approximated from OICA (2015) and the ICCT Roadmap model (See ICCT, 2015). Generally these overall light-duty vehicle sales growth projections involve approximately 0.5% annual vehicle sales growth in the United States, Japan, and Europe, and 3-4% annual sales growth elsewhere.

Based on the government goals for the potential deployment of electric vehicles, as modified above, annual and cumulative sales are estimated through 2025. Figure 3 summarizes the annual electric vehicle sales in the markets with associated goals. As shown, the total annual electric vehicle sales increase from less than a half million per year in 2015 to above 7 million per year in 2025. The targets of the eleven founding participants of the International Zero

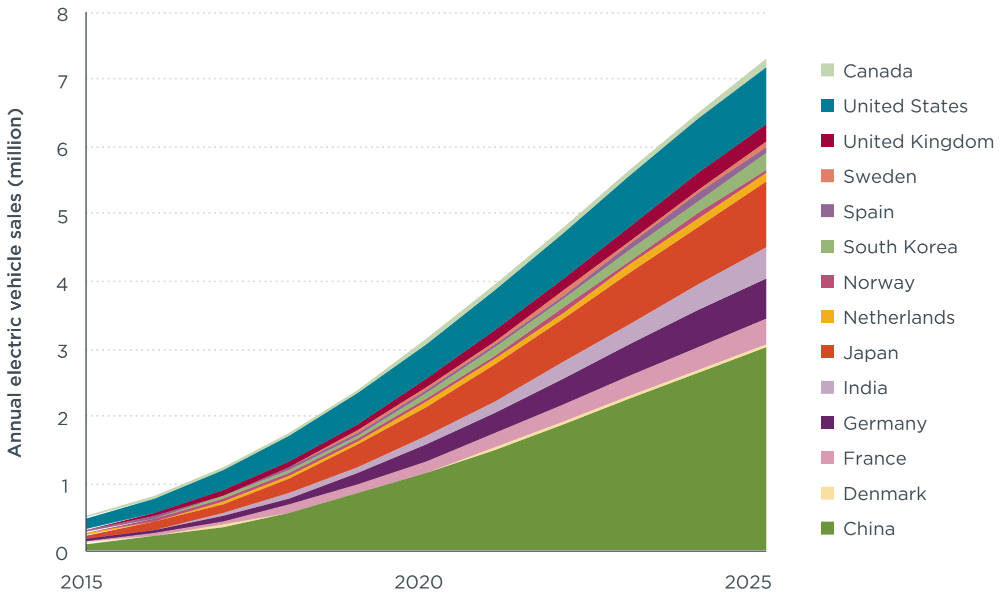

Figure 3. Annual sales of electric vehicles in markets with electric vehicle deployment goals through 2025

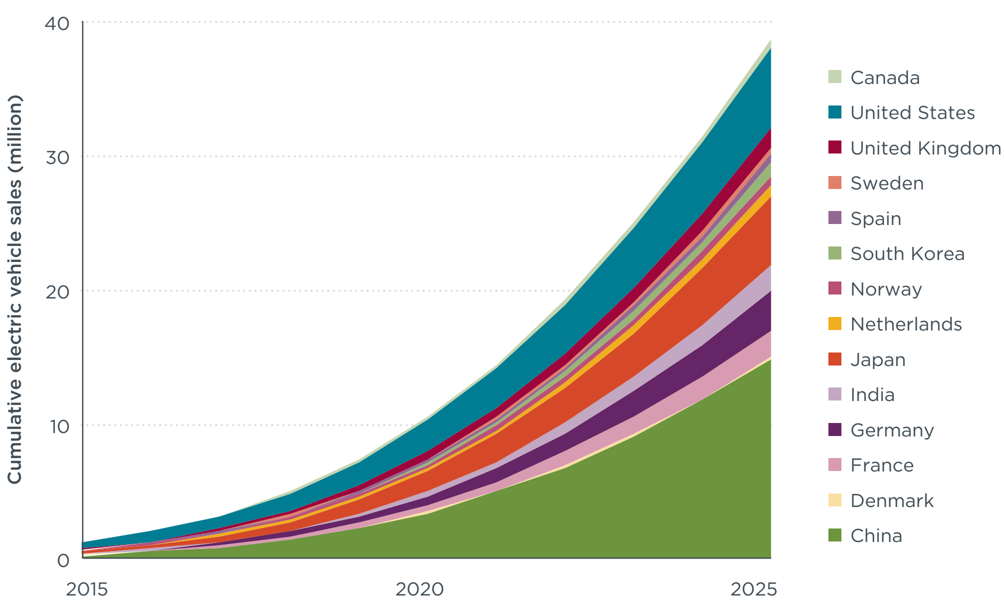

Figure 4. Cumulative deployment of electric vehicles in markets with electric vehicle goals through 2025

Emission Vehicle Alliance (ZEV Alliance) — California, Connecticut, Maryland, Massachusetts, the Netherlands, Norway, Oregon, Quebec, Rhode Island, the United Kingdom, and Vermont — represent about 1 million annual 2025 electric vehicle sales. The markets that contribute the most to the potential increase in annual electric vehicle sales in 2025 are China (approximately 3 million), Japan (1 million), Germany (0.6 million), the eight United States (0.5 million), France (0.4 million), and the United Kingdom (0.3 million). As a share of approximately 120 million total global light-duty vehicles, a total of 7 million zero-emission vehicles would represent an 8% share of new global vehicle sales in 2025.

Figure 4 shows the same electric vehicle deployment as depicted above, but as the *cumulative* deployment of new electric vehicles through 2025. As shown, the total cumulative electric vehicle sales from markets with associated goals increases from about one million in 2015 to above 38 million in 2025. The ZEV Alliance founding participants account for 6 million of the 38 million cumulative electric vehicles. Combining the ZEV Alliance targets with electric vehicle targets of China, France, and Germany would amount to 26 million of the 38 million cumulative electric vehicles through 2025. As shown in the figure, the markets that contribute the most to the potential increase in cumulative sales are China (14 million), Japan (5 million), the eight U.S. states (3 million), Germany (3 million), France (2 million), and the United Kingdom (1.5 million).

LONG-TERM ELECTRIC VEHICLE SCENARIOS

Research indicates that in order to meet long-term climate change mitigation targets, rapid global adoption of electric vehicles over the next several decades is needed. Many studies have determined that to achieve climate change stabilization goals (e.g., 450-ppm, 2°C increase) a large-scale shift from the internal combustion of petroleum fuels to electric-drive will be needed (e.g., see, IEA, 2012; Deetman et al., 2013; Greenblatt, 2015; Williams et al., 2011). The studies imply that efficiency standards, attempts at curbing transport activity, and availability of sustainable low-carbon biofuels will likely be insufficient for the transportation sector to meet its global carbon reduction goals. Furthermore, these analyses of 2050 scenarios indicate that electric-drive vehicles powered by ultra-low carbon electricity or hydrogen will be needed and will eventually have to become dominant for passenger vehicles.

Many studies have, in turn, sought to model, forecast, analyze, and project the deployment of electric vehicle sales under various market and policy conditions (See Lutsey, 2015b)[1]. In those studies, as well as throughout this paper, electric vehicles or "zero emission vehicles" include the three major technology types (i.e., plug-in hybrid, full-battery electric, and hydrogen fuel cell). Several studies (e.g., NRC, 2013b) indicate that fuel cell electric vehicle technology might have greater potential in the long-term 2050 context. However, most of the recent trends and data on electric vehicles are more exclusively focused on plug-in electric vehicles, due to their increased availability, marketing, and sales in recent years. Generally studies that assume greater technical advancement (e.g., in battery technology) and increased policy support (e.g., R&D, infrastructure, regulation) find 20% to over 50% electric vehicle shares are possible in leading electric vehicle markets in the 2025-2030 timeframe. However, studies that considered lesser technical advancement and policy support generally found that the electric vehicle market, in various countries and globally, could remain as low as 5-10% in the 2025-2030 timeframe.

For this analysis, a full transition to electric-drive by highly motivated markets over the next several decades is projected. The premise is that electric-drive policy commitment from the leading governments in 2015 will persist for several decades, due to strong support for climate change mitigation, petroleum use reduction, clean air, and industry leadership. This analysis' electric-drive vehicle deployment scenarios are predicated upon years of regulatory, fiscal, non-fiscal, infrastructure, and public awareness support by many governments at the national and local levels. The analysis is also predicated upon the next-generation electric vehicle models continuing to see technology improvements, cost reductions, and sustained marketing and deployment efforts by automobile manufacturing companies and dealers. Based on these assumptions, this scenario represents the maximum plausible global electric-drive deployment through 2050.

Figure 5 illustrates the projected penetration of electric-drive vehicles as a share of new vehicle sales across various major automobile markets. In essence, these electric vehicle shares connect the achievement of near- and mid-term 2020-2025 electric vehicle goals (per above Figure 2), and long-term goals for a nearly fully electric-drive fleet in the 2040-2050 timeframe. Under the uncertainty, the markets' differing trajectories are meant to be illustrative, approximated based on the differing current and future government ambitions for the electric vehicle market. The "rest of world" is approximated simply as following the average of the leading markets' electric vehicle uptake, delayed by twelve years. The global electric vehicle new sales share that matches the scenario assumptions, as shown, is 15% in 2030 and surpasses 50% by 2040. It is emphasized that this progression for advanced electric-drive technology over the next several decades would represent a revolutionary shift in the automobile market that is without a comparable precedent.

VEHICLE TECHNOLOGY AND CARBON EMISSIONS

This section describes how CO_2 emissions from vehicle types are projected based on expected technology improvements.

1 BCG, 2011; Bharat Book, 2014; CARB, 2011; Element Energy, 2013; ETS Insights, 2014; Greene et al., 2013, 2014; IEA, 2011; IEA, 2013; JD Power, 2013; Malins et al., 2015; McKinsey, 2014; Navigant, 2013, 2014; NRC, 2013; Roland Berger, 2011

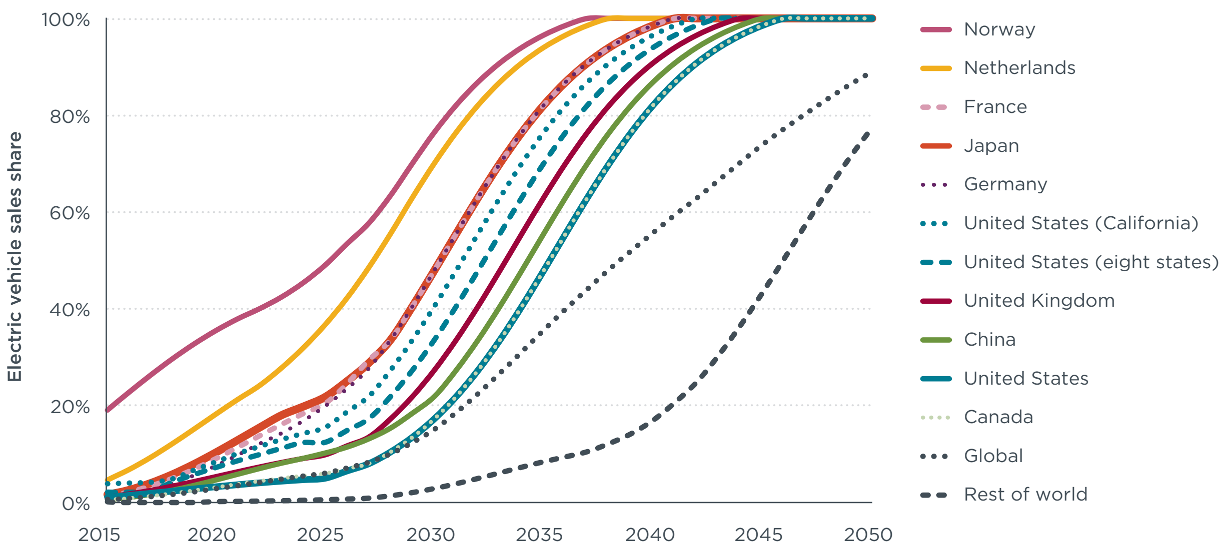

Figure 5. Share of new passenger vehicle sales that are electric vehicles for selected markets, as assumed for this assessment

The section includes summaries of the assumptions for incremental vehicle efficiency improvements from conventional vehicles, as well as vehicle technology and carbon intensity reductions related to plug-in electric and hydrogen fuel cell vehicles.

Conventional vehicles. Many data sources are used in this analysis of vehicle use and fuel lifecycle CO_2 emissions. Vehicle efficiency is based on the ICCT global standards work through 2020 and 2025 for adopted standards (ICCT, 2015). After adopted standards are implemented, assumed continued efficiency standards for conventional vehicles are estimated as 3%/year through 2030 and 1.5%/year for 2031-2050. Near-term efficiency improvements are based on 2020 and 2025 regulation trajectories; longer-term reduced efficiency improvement rates are based on internal combustion vehicle efficiency data from the National Academies' long-term technology study (NRC, 2013). Importantly, on-road fuel consumption is assumed to be approximately 25% higher than the regulated test cycle fuel use.

Countries without standards are estimated here to follow a similar trajectory but with a time delay compared to markets with existing efficiency standards. Petroleum fuel lifecycle emissions, consistent with lifecycle numbers associated with fuel regulations in the United States, California, and Europe, are approximately 22% of vehicle and fuel lifecycle emissions. Generally this means CO_2 exhaust emissions are approximately 8.8 kilograms per gallon of gasoline, and lifecycle CO_2 emissions are 93 grams per megajoule of fuel. For simplicity, this assumption is held constant throughout the analysis; potential shifts from the utilization of alternative fossil fuels or biofuels with varying carbon contents are not considered in this assessment.

Plug-in electric vehicles. Plug-in electric vehicles' climate change benefits are estimated according to their relative carbon dioxide (CO_2) emission reduction compared to similar conventional vehicles emissions over time. This requires estimations of electric vehicles efficiency improvements over time (based on incremental on-vehicle efficiency improvement), and the carbon intensity of electricity generation.

Figure 6 shows the assumed grid decarbonization trend for this analysis (Based on ENTSOE, 2015; Ecofys, 2015; U.S. EPA, 2014; IEA, 2014). To approximate the carbon emission impact of the electric-drive vehicles' impact, average grid CO_2 emissions are applied to the various markets from several sources. The primary sources for 2011-2012 grid emissions, the breakdown by energy source, and carbon emissions by energy sources are Ecofys (2015), ENTSOE (2015), and U.S. EPA (2014). The shift in carbon emissions through 2035 is taken from the International Energy Agency's *World Energy Outlook* (IEA, 2014). IEA presents data on a Business As Usual, New Policy, and 450 Scenarios. The middle New Policy scenario is used to estimate a plausible central case for electricity energy source decarbonization in this paper. Results from the two other grid scenarios are also shown below to illustrate lower and higher emissions cases. The central scenario includes a shift in China's average grid mix from 79% to 55% coal (and from 19% to 38% renewable plus nuclear) over the 2011 to 2035 period. As shown, the average European grid is the least carbon intensive; the shift is from 49% to 66% low-carbon (i.e., renewable plus nuclear) from 2011 to 2035. After 2035, a 3% per year reduction in carbon intensity is assumed in all regions.

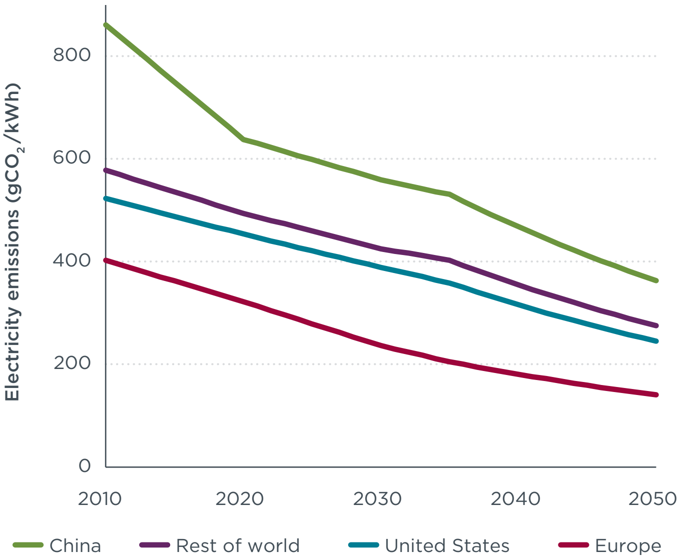

Figure 6. Average electricity grid carbon emissions assumed in this assessment

Regional electricity grid mix averages are used due to data availability and long-term uncertainties. Although electric vehicle sales trajectories are analyzed by individual European countries (per Figure 5), the electric grid for Europe is modeled in aggregate, due to frequent cross-border grid transmission (see ENTSOE, 2015) and the difficulty in accurately modeling those electricity imports and exports for the various member states. Similarly, the United States national average grid emissions are used as a starting point. However, it is noted that the majority of EV sales are in states (California and the other Eight-State-MOU states) where the carbon intensity of electricity generation is generally well below the United States average (see U.S. EPA, 2014). This assessment thus tends to underestimate carbon reductions from electric vehicles in the United States. Issues about marginal versus average grid emissions are beyond the scope of this work and add uncertainty.

Several additional assumptions are applied to connect grid carbon emissions to vehicle energy use. Electric vehicle efficiency is assumed to be 0.34 kilowatt hours (kWh) per mile in 2015, matching the electricity consumption of the Nissan Leaf. Electric vehicle efficiency improvements are incorporated in new vehicles at a rate of 1% per year reduction in electricity-per-mile to reflect increased efficiencies in the motor, generator, regenerative braking, lightweighting, and aerodynamics areas, approximated from NRC (2013). Electric vehicle charging efficiency of 85%, upstream transmission and distribution losses of 7%, and additional upstream fuel extraction emissions of 6% are assumed (as in U.S. EPA and NHTSA, 2012).

Figure 7 summarizes the fuel and vehicle use cycle CO_2 emissions from average internal combustion and battery electric vehicle emission rates based on the above assumptions. As illustrated, new internal combustion vehicles show marked reductions from 2013 through 2030. Electric vehicles have average CO_2 emissions that are below internal combustion vehicles in 2013, and electric vehicle emissions remain well below new 2030 internal combustion vehicles in 2030. This is the case due to more rapid CO_2 reduction from grid electricity than from efficiency improvements in internal combustion vehicles (shown above in Figure 6).

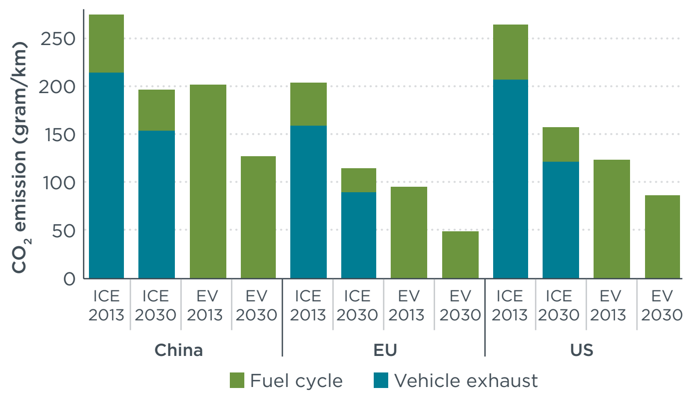

Figure 7. Vehicle exhaust and fuel-cycle emissions from conventional internal combustion engine and battery electric vehicles in select markets

The above assumptions apply to battery electric vehicles. Plug-in hybrid electric vehicles are also assumed to be deployed at numbers similar to battery electric vehicles (see below for relative penetration rates). Plug-in hybrid electric vehicles are assumed to be powered by electricity for approximately 40% of all their travel in 2015. The highest-selling plug-in hybrid Chevrolet Volt, which also has the highest all-electric range among popular plug-in hybrids, has averaged about 70% electricity-powered miles through over one billion total miles traveled (GM-Volt, 2014). Models with lower all-electric range tend to be powered from electricity less frequently, but there is no definitive data source. The percent of miles that are powered by grid electricity is estimated to increase as new plug-in hybrid electric vehicle models continue to increase their electric range over time. Here the electric-travel percent among plug-in hybrid electric vehicles is assumed to increase at about 2% per year in new vehicles, reaching 50% in 2027 and approximately 80% in 2050.

Hydrogen fuel cell vehicles. Fuel cell vehicles offer substantial CO_2-reduction benefits versus conventional vehicles on account of having about double the efficiency and due to their potential to be fueled by lower-carbon energy sources. In this assessment the average 2015 fuel cell on-road vehicle efficiency is estimated to be 60 miles per kilogram of hydrogen (equivalent to 60 miles per gallon gasoline equivalent). This approximately matches the several hydrogen fuel cell vehicle models that have been available in the United States (U.S. EPA, 2015). Future new vehicles are assumed to consume 1% per year less hydrogen per mile due to efficiency improvements for new models through 2050. For analyzing the fuel carbon intensity, fuel cell vehicles' hydrogen fuel is initially analyzed as from natural gas, but the fuel source shifts toward renewable sources incrementally through 2050. The carbon intensity in 2010-2015 of 100 gram CO_2 per megajoule is reduced by 40% in 2030, and by 80% in 2050, based initially on CARB fuel carbon intensities (CARB, 2012) and decreasing at approximately 4% per year. Figure 8 summarizes hydrogen fuel cell vehicles' carbon emissions in this analysis, incorporating their efficiency benefits and a shift to lower-carbon fuels. As illustrated, shifting to lower-carbon hydrogen sources will be key for fuel cell vehicles to continue to offer greater carbon-reduction benefits compared to internal combustion vehicles in the 2030 timeframe.

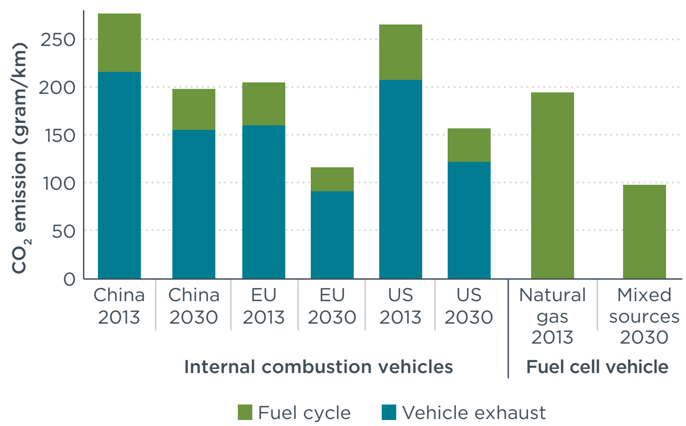

Figure 8. Vehicle exhaust and fuel-cycle emissions from average internal combustion engine and hydrogen fuel cell vehicles

Technology mix over time. As described above, there are a myriad of studies projecting the potential future deployment of various electric-drive vehicle types. In the absence of consensus or clarity about the mix of battery electric vehicle, plug-in hybrid electric vehicles, and hydrogen fuel cell vehicles that might prevail, an increasing mix of each is included as shown in Figure 9. Two illustrative technology paths are depicted, one for "leading markets" for electric vehicles and one for "other markets." The ZEV Alliance markets are projected to follow a more aggressive transition to electric-drive technology, approximately shown on left "Leading" side of the figure. Compared to the leading technology path shown, several European countries are projected to be several years accelerated (e.g., Norway and Netherlands are more accelerated), while the markets of the United States and China,

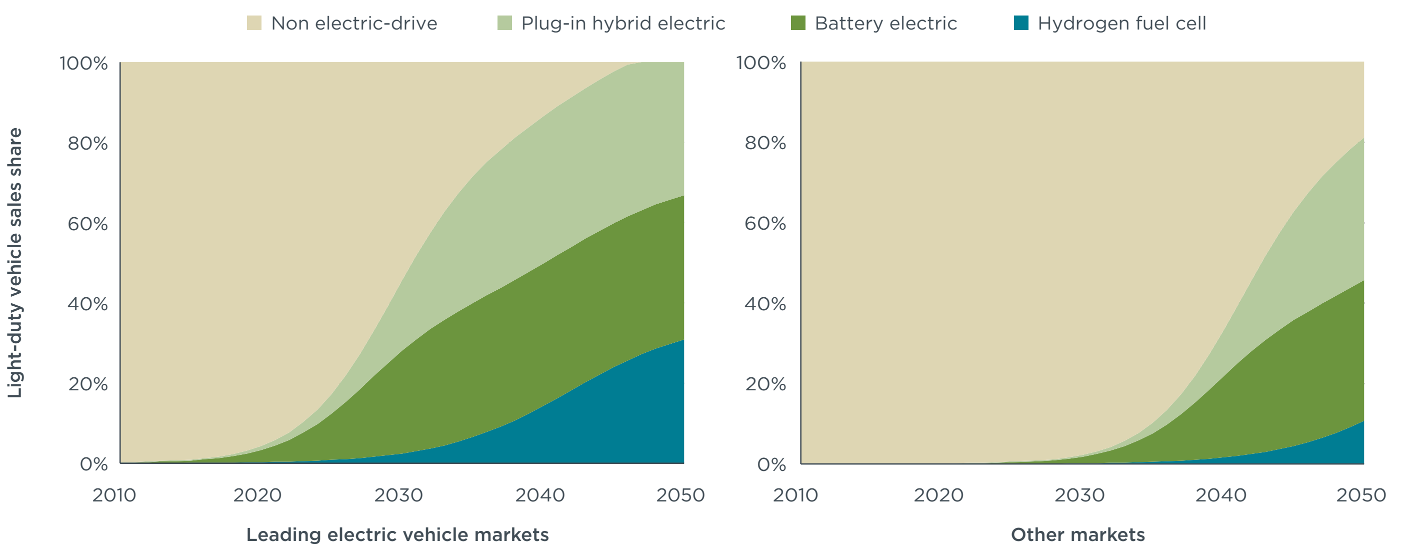

Figure 9. Illustrative sales shares for plug-in hybrid, battery electric, and hydrogen fuel cell vehicles through 2050, for leading electric vehicle markets and other markets

though still leaders, take several additional years to meet their goals as described above (See Figure 5). The "Other markets," represented by the right side of the figure, lag the average "leading markets" progression by twelve years as discussed above, and therefore have relatively limited electric vehicle penetration by 2030. On the "Leading" side of the figure, battery electric vehicle share increases most quickly in the 2020-2035 timeframe, followed by plug-in hybrid share in the 2025-2040 timeframe, followed by fuel cell vehicle growth in the 2040-2050 timeframe.

III. Results

This section summarizes the results from the above analysis. The results present the emission reduction impacts from markets around the world achieving government goals for electric vehicle deployment, including a long-term scenario for electric-drive vehicle market success. The results are first presented for several major regions, and then for the global fleet at large.

As shown in Figure 10, substantial greenhouse gas emissions result from the vehicle technology scenarios analyzed in this paper. Emission trajectories are presented for a business-as-usual scenario, an increased efficiency scenario, and an electric-drive penetration scenario to isolate the impacts from electric-drive vehicles. Three cases for grid-decarbonization are shown within the electric-drive penetration scenario. Europe, China, and the United States are shown in the figure, as these are the regions with the greatest CO_2 impact from electric vehicles. Because the electric-drive vehicle penetration in other regions is assessed as following these markets by a decade or so, the climate impacts from the other markets is substantially slower. Although the objective of this analysis is to quantify electric-drive vehicle carbon benefits, a key result depicted in the figure is that a larger share of the carbon reductions result from continued efficiency improvements in the conventional vehicle fleet. Electric vehicles, although continually offering lower-carbon emissions, are slower in displacing the conventional vehicle fleet; as a result, their climate benefits become more prominent over time.

By 2030, increased deployment of electric vehicles in Europe and the United States are each projected to offer the potential of 20-25 million metric tons per year in CO_2 reduction benefits. Electric vehicles in China offer more than those two leading markets combined in potential climate benefits. Despite China's higher carbon-intensive grid and lower electric vehicle market share, the potential benefits in the electric-drive penetration scenarios compared to BAU in billion tons CO_2 reduction are greater due to the relatively high carbon intensity of conventional gasoline vehicles as well as the much larger overall vehicle sales. Conversely, the potential carbon reductions from electric-drive penetration in Europe are lower due to lower vehicle sales in that region. Other markets around the world also offer the potential for approximately 20 million tons of CO_2 reduction, with the potential being more limited based on a variety of factors, including lower vehicle sales and therefore smaller market size (e.g., Canada), a lesser difference between conventional and electric vehicles CO_2 emissions (e.g., Japan), and a slower projection for accelerated electric-drive vehicle sales (e.g., in all countries not analyzed in Figure 5).

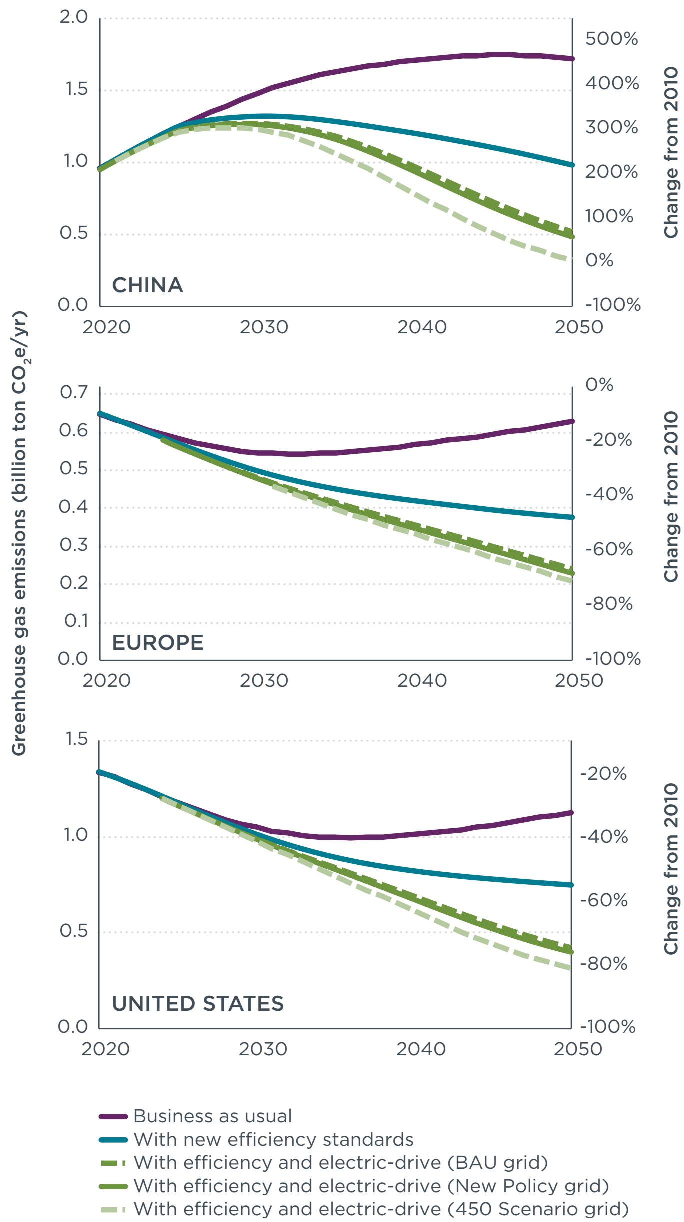

Figure 10. Greenhouse gas emissions for conventional vehicles (business as usual and with efficiency standards), including increasing amounts of electric vehicles in China, Europe, and United States from 2020 through 2050

As illustrated, the electric vehicle carbon reduction benefits are far greater in the 2040-2050 timeframe than in the 2020-2035 timeframe; this is a consequence of changes in the rate of electric-drive vehicle penetration in the fleet, slow turnover of the fleet, and grid decarbonization over time. The trajectories of China, Europe, and the United States differ quite substantially. The major difference is due to the rapid growth of vehicle ownership and travel in China compared to the United States and European markets. Under the most aggressive vehicle efficiency and electric-drive deployment scenario, China is projected to see its light-duty vehicle emissions reduced approximately back to 2010 vehicle CO_2 levels by 2050 in this analysis. The Europe and United States scenarios show the potential to reduce vehicle CO_2 emissions by 50-80%.

Figure 11 summarizes global greenhouse gas emission impacts from the three main scenarios: (1) Business as usual, including already-adopted vehicle efficiency regulations; (2) With new efficiency standards that continue to increase vehicle efficiency over time; (3) With extensive deployment of electric vehicles on increasingly low-carbon energy sources. The same three cases for grid decarbonization are shown for the third scenario as in Figure 10. As shown in the figure, efficiency standards are critical in delivering emission reductions in the nearer term to offset the travel demand growth. Over the long-term, electric vehicles are key to delivering deeper emission reduction that are consistent with long-term market growth and climate stabilization goals — for example a 50-80% reduction in markets with less growth, and stabilizing emissions in high-growth markets like China.

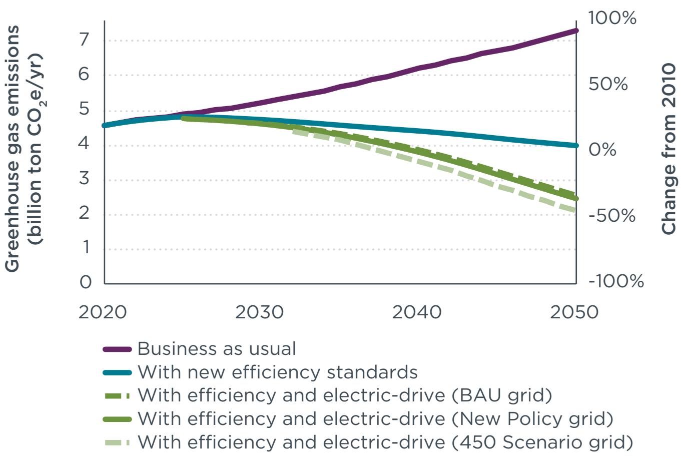

Figure 11. Global greenhouse gas emissions from business-as-usual, increased efficiency, and increased electric light-duty vehicle fleet

As illustrated by the three scenarios, without substantial vehicle efficiency and electric-drive vehicle growth that is sustained globally through 2050, light-duty vehicle greenhouse gas emissions are projected to approximately double from 2010 to 2050. New efficiency standards without electric-drive growth is projected to result in keeping light-duty CO_2 emissions at about 2010 global levels through 2050. Going beyond the efficiency scenario, the potential for emission reductions from electric vehicles is substantial. Electric-drive vehicle technology brings emission reductions of 125 million metric tons of CO_2 per year in 2030 under the central scenario analyzed here (110 and 180 million metric tons under the other two grid scenarios). For 2050, the potential annual emission reductions increase to 1.5 billion metric tons CO_2 per year by 2050 (1.4 and 1.8 billion metric tons under the other two grid scenarios). Based on this analysis, the transition to a global electric vehicle fleet achieves approximately 40% lower carbon emissions than a highly efficient conventional combustion fleet (and 70% lower carbon emission than a business-as-usual fleet) in 2050.

Figure 12 summarizes the result from this analysis of the greenhouse gas emission reduction potential from achieving near-term and long-term government goals for the deployment of electric vehicles, increasingly powered by low-carbon energy sources, through 2050. Here, emission reductions from electric vehicles specifically are shown as the difference between the new efficiency standards scenario and the electric-drive scenario above (central grid scenario). As indicated, in the earlier years electric vehicle benefits are limited by electric vehicle sales growth and fleet turnover, but the climate benefits increase greatly over time. The potential emission reductions in 2030 are 125 million metric tons CO_2, with the vast majority of those effects being in leading electric vehicle markets of China, Europe, and the United States. As shown, the potential long-term carbon emission-reduction benefits from electric vehicles are more substantial, amounting to 1.5 billion metric tons CO_2 per year in 2050, with the benefits more globally distributed across China, Europe, the United States, and the rest of the world.

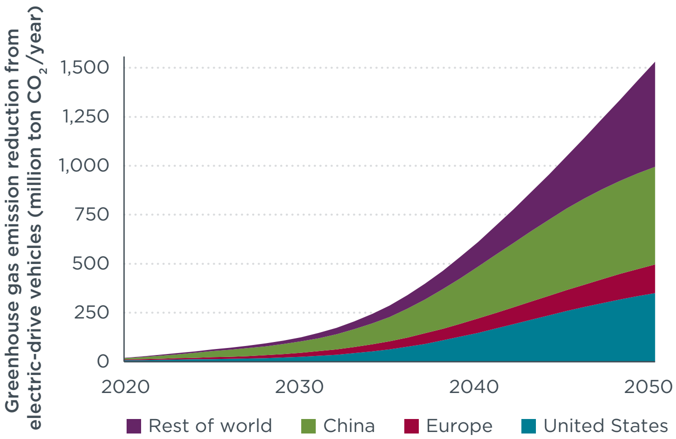

Figure 12. Global greenhouse gas emission reduction from increased penetration of electric vehicles through 2050

IV. Conclusions

A key objective of this paper is to analyze the potential emission reduction impacts from markets around the world that are achieving government goals for electric vehicle deployment, including a long-term transition to an electric-drive fleet. The analysis compiles data from various jurisdictions on electric-drive vehicle deployment goals, factors in plausible market constraints in the near-term, projects long-term vehicle technology paths, and analyzes the expected CO_2 reduction potential based on a shift to electricity and hydrogen energy sources.

The analysis quantifies the potential climate benefits from the most proactive governments meeting their long-term goals to decarbonize passenger vehicles with increased penetration of electric-drive. It is emphasized that this progression for advanced electric-drive technology over the next several decades would represent a revolutionary shift in the automobile market that is without a comparable precedent. Such a transformation of the market will require sustained efforts from industry to achieve the necessary manufacturing scale, and from governments to provide the right combination of policy, infrastructure, and consumer support.

The results from the analysis provide several insights regarding near-term and long-term electric-vehicle deployment goals and their potential climate benefits. Drawn from this paper's results are two main conclusions:

> ***Governments' electric vehicle targets amount to more than 30 million cumulative electric vehicles by 2025.*** In 2014, the share of new vehicles that are plug-in electric vehicles is about 0.5%—2% in most major vehicle markets, although a number of particular markets are showing substantially greater penetration. Allowing for near-term supply constraints, electric vehicle sales share could increase to at least 10%—15% across leading markets around 2025. This would amount to a massive deployment of electric vehicles and will require improvements in the electric vehicle supply chain, far greater auto manufacturing scale, lower cost next-generation electric vehicle models, and sustained regulation and support from governments.

> ***Electric vehicles' potential climate benefits could increase dramatically over time, from over 125 million tons CO_2 per year in 2030 to over 1.5 billion tons CO_2 per year in 2050***. The carbon mitigation would result from more electric vehicles entering the fleet while lower-carbon energy sources become widely available. Electric vehicle technology allows the global fleet to achieve approximately 40% lower carbon emissions than a highly efficient conventional combustion fleet (and 70% lower carbon than a business-as-usual fleet) in 2050. Matching the earlier projected electric vehicle deployment, electric vehicle climate benefits will initially be highest in European nations and in select United States regions. Over the long-term, potential electric vehicle climate benefits are greatest in China and other emerging automobile markets.

This analysis points toward future research, as well as broader implications for global electric vehicle collaboration. First, continued research into the underlying factors of this analysis could help assess the sensitivity of the results to various vehicle technology, lifecycle emission, travel activity, and policy assumptions across global markets. Second, there are questions related to achieving the required global scale to move toward an increasingly electric-drive fleet and the associated policy involved. This work indicates that leading climate mitigation policymakers could include electric vehicles as a core component of their local, state, national, and multi-government climate commitments. Establishing a global target to move toward all zero-emission passenger vehicles over the 2025 to 2050 time frame would provide a common vision and set clear signals for the pace of technology development and the amount of resources that will be needed. Multi-government collaboration on early lessons, emerging best practices, and policy effectiveness would help prioritize government actions to further increase zero-emission vehicle uptake and use.

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