How Cost-Effective Are Electric Vehicle Subsidies in Reducing Tailpipe-CO₂ Emissions? An Analysis of Major Electric Vehicle Markets

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Key Points

Plug-in electric vehicle (PEV) deployment can help eliminate tailpipe carbon dioxide (CO₂) emissions from passenger cars. Subsidies represent one of the most common policy levers for promoting PEV adoption, and recent research suggests this approach is partly effective. However, it is unclear how cost-effective PEV subsidies are in reducing tailpipe-CO₂ emissions. We address this question by analyzing and comparing the major PEV car markets, including China, the United States, and nine European countries, from 2010 to 2017.

We find that in 2017, PEV adoption in these 11 countries avoided 5.63 million tonnes of tailpipe-CO₂ (0.51% in relative terms). This represents an upper bound and does not account for upstream and manufacturing-related emissions. By comparison, between 2008 and 2016, the European Union emissions trading system had cut CO₂ output by an average of 133 million tonnes per year.

We estimate that the subsidy cost per tonne of tailpipe-CO₂ avoided can reach \$1,600, with the highest cost for China, followed by Denmark and Norway. The effective cost increases further when the actual extent of PEV sales induced by the subsidies is considered.

Our findings highlight the need to design more cost-effective PEV subsidies than those examined in this study, which are more than an order of magnitude more expensive than the social cost of carbon. This is especially crucial in current times when governments are allocating billions of dollars to promote PEV sales as part of COVID-19 stimulus packages.

Summary

The transportation sector accounts for 24% of global greenhouse gas (GHG) emissions (IEA 2020). Road transport is the most utilized mode because of its convenience (Van Essen 2008). However, it is also the most emissions intensive mode, accounting for 75% of global transport GHG emissions, with roughly 44% coming from road passenger vehicles alone (IEA 2020).

One way to lower passenger vehicle carbon dioxide (CO₂) emissions is through deployment of lower- and zero-tailpipe emission technologies including plug-in electric vehicles (PEVs) and hydrogen fuel cell electric vehicles¹ (Kalhammer et al. 2007). Demand-side fiscal policies represent one of the most common policy levers for promoting deployment of PEVs (IEA 2020; Langbroek, Franklin, and Susilo 2016; Lévy, Drossinos, and Thiel 2017; Lieven 2015). However, early evidence from the light duty vehicle (LDV) markets of the United States (U.S.) and Canada suggests that promoting deployment of PEVs through subsidies is expensive (Sheldon and Dua 2018, 2019; Azarafshar and Vermeulen 2020; Xing, Leard, and Li 2019; DeShazo, Sheldon, and Carson 2017). This paper explores the evolution of tailpipe-CO₂ emissions avoided as well as subsidy cost per tonne of tailpipe-CO₂ avoided across major PEV markets from 2010 to 2017. In particular, we focus on China, the U.S., and nine European countries, which are currently the leaders in the PEV market, to determine the spatio-temporal evolution of the subsidy impact and cost-effectiveness.

The impact of PEV subsidies on tailpipe-CO₂ emissions depends not only on the number of PEVs sold, but also on the extent to which they displace internal combustion engine vehicles (ICEVs) (Sheldon and Dua 2018). We utilize a modified detailed version of the conventional counterfactual approach to estimate the tailpipe-CO₂ emissions of the replaced vehicle fleet in the absence of the

subsidy (Sheldon and Dua 2018). We assume that in the absence of the subsidy, the PEV buyer would have bought the average ICEV of the same body type as the PEV (Holland et al. 2016; Archsmith, Kendall, and Rapson 2015; Graff Zivin, Kotchen, and Mansur 2014; Sheldon and Dua 2018). It is worth noting that previous research incorporating choice-model-based counterfactuals suggests that PEVs tend to displace higher efficiency vehicles (Xing, Leard, and Li 2019; Muehlegger and Rapson 2020). Thus, the extent of tailpipe-CO₂ emissions reduction found by our conventional counterfactual approach represents an optimistic estimate; thus our estimates of the cost per tonne of tailpipe-CO₂ avoided are on the lower side.

PEV subsidy effectiveness depends on the extent of tailpipe-CO₂ avoided and the elasticity of PEV market share with respect to PEV subsidy. We find that in 2017, the total tailpipe-CO₂ avoided through PEV adoption in these 11 countries was 5.63 million tonnes (0.51% in relative terms). We also estimated the annual percentage of tailpipe-CO₂ avoided from the new vehicle fleet for each country as a result of PEV adoption. Our findings suggest that the percentage of tailpipe-CO₂ avoided through PEV substitution varies linearly with PEV market share.

Based on tailpipe-CO₂ avoided and subsidy costs, we find that a conservative estimate of the cost per tonne of tailpipe-CO₂ avoided can reach \$1,600 on PPP basis in 2010 U.S. dollars (2010 US\$). Considering the variation across different countries, we find that the cost per tonne varies almost linearly with subsidy (as a percentage of vehicle price) for PEVs, with the highest cost per tonne seen for China, followed by Denmark and Norway.

The policy cost is more than an order of magnitude higher than the social cost of carbon (Rennert and Kingdon 2019). The estimated cost per tonne of tailpipe-CO₂ avoided becomes even higher if we

consider the actual extent of electric vehicle sales induced by the subsidies, i.e., elasticity of PEV market share with respect to PEV subsidies.

The high cost of tailpipe-CO₂ emissions reduction through PEV subsidy policies warrants research into and adoption of innovative subsidy designs to improve cost-effectiveness. Innovative targeted PEV subsidy designs could be incorporated into

COVID-19-related economic stimulus packages that many governments are currently considering (CNN Business 2020; Financial Times 2020a, 2020b, 2020c; AVERE 2020; Reuters 2020; Caixin 2020). Targeted designs based on either consumer income or vehicle price represent viable cost-effective alternatives, as suggested by recent research (Sheldon and Dua 2019a, 2019b, 2020; Xing, Leard, and Li 2019).

Background

Internal combustion engine vehicles emit both smog-forming pollutants and GHGs from their tailpipes. CO₂ makes up roughly 99% of total tailpipe-GHG emissions (U.S. EPA 2019). BEVs, by contrast, produce no tailpipe emissions. The emissions associated with the production and distribution of energy used to power vehicles are known as ‘upstream emissions’ (U.S. DOE 2021).² While upstream emissions related to electricity generation can contribute significantly to the total CO₂ footprint of electric vehicles, in this analysis we focus only on tailpipe-CO₂ emissions. This is for two reasons. First, all countries consider tailpipe-CO₂ emissions only in their vehicle CO₂ emission standards,³ and have separate policies for reducing the CO₂ emissions associated with their electricity generation sectors. Second, the aim of this analysis is to estimate and compare the cost-effectiveness of different countries’ PEV subsidy policies in reducing CO₂ emissions from passenger transportation. Incorporating upstream CO₂ emissions in our analysis without accounting for the subsidy costs associated with cleaning that particular country’s power sector would create unfair comparisons of total subsidy cost per tonne of CO₂ avoided across different countries. This is because most countries have also implemented aggressive demand-side fiscal policies for reducing electricity sector emissions. A full-scale analysis incorporating the total CO₂ savings and subsidy costs associated with cleaning both the passenger transportation and power sectors is beyond the scope of this paper. A separate and growing literature exists on the cost per tonne of CO₂ avoided in the power sector through subsidies for promoting adoption of renewable electricity generation technologies (Gillingham and Stock 2018).

Given the lack of literature on comparisons between PEV markets in different countries, we identified the following research questions for detailed investigation:

How do the PEV and non-PEV vehicle fleet characteristics compare across the identified markets and how have they evolved over time?

How do the PEV market shares and subsidies for PEVs in these different countries compare with one another and how have these characteristics evolved over time?

What vehicles do PEVs replace and how do vehicle fleet characteristics change as a result?

How much tailpipe-CO₂ emission has been avoided through PEV adoption in these different countries, in both absolute and relative terms?

What is the subsidy cost per tonne of tailpipe-CO₂ avoided and how does it vary across the different countries?

How do effective CO₂ reduction costs change when PEV sales induced by subsidies are taken into account?

How can we improve the cost-effectiveness of subsidy policies, especially for those that are a part of COVID-19 stimulus packages?

What policy lessons can different countries learn from one another?

This paper contributes to the existing PEV subsidy literature, which primarily focuses on individual markets while considering datasets covering only a few years, by making cross-country comparisons and looking at the longer-term temporal evolution. By comparing countries with PEV market shares ranging from less than 1% to 38%, this paper provides a broader view on trends and how these metrics might evolve as the PEV adoption increases in countries with currently low PEV market shares.

Data

Our main dataset is a rich panel of passenger car sales and characteristics for major car markets, obtained from JATO Dynamic Limited. It includes sales numbers, prices, and product characteristics for every new passenger car sold during 2010-2017⁴ in the U.S., China and nine European countries: Norway, the Netherlands, Sweden, Italy, Spain, Great Britain, Denmark, France, and Germany.

Each car is defined according to make, model, powertrain type, and body type, e.g., Honda Accord hybrid sedan. Sales are defined as annual new car registrations. Prices are manufacturer suggested retail prices (MSRPs), excluding any taxes. Car characteristics include measures of vehicle size (wheelbase, width, length, height and curb weight), horsepower (hp), and tailpipe-CO₂ emissions.

Summary Statistics

Figures 1, 2 and 3 below provide summary statistics for various vehicle attributes broken down by country and year.

Figure 1 includes new vehicle sales-weighted fleet dimensions: (a) length, (b) width, (c) height, and (d) wheelbase.

Figure 2 shows new vehicle sales-weighted fleet average for four attributes: (a) tailpipe-CO₂ emissions, (b) MSRP, (c) curb weight, and (d) horsepower.

Figure 3 shows the evolution of the (a) PEV, (b) battery electric vehicle (BEV), and (c) plug-in hybrid electric vehicle (PHEV) market shares in each country over time together with the average PEV subsidy amounts.

Among the different countries, the U.S. new vehicle fleet is the largest, tallest, heaviest, strongest (in hp terms), and dirtiest (in terms of tailpipe-CO₂ emissions). Conversely, the fleets in Denmark and the Netherlands are the smallest, shortest, lightest, weakest, and cleanest for most years.⁵ In terms of average vehicle cost (excluding taxes), the fleets in Norway, Sweden and Germany tend to be the priciest in most years, though over time the U.S. fleet became more expensive and overtook its European counterparts in 2015 and 2016. While all the fleets are becoming greener over time (in terms of PEV market share), Norway has the greenest, followed by the Netherlands and Sweden. The market shares for both BEVs and PHEVs are rising over time, with no clear trend of one powertrain type dominating the other.

Charts summarizing the statistics for the PEV fleets in each country are given in the appendix. As shown in figures A1 and A2, in recent years, China's PEV fleet is the lightest, cheapest, cleanest, and smallest, while those of the U.S. and the Netherlands are relatively heavier, costlier, dirtier, and bigger.⁶ Figures A3 and A4 demonstrate that for each country and in all years, PEV fleets are costlier and cleaner than the overall fleets.

For European countries, we obtain the average subsidy amounts per PEV from Münzel et al. (2019). For the U.S., we procured federal and state subsidy amounts per PEV from the U.S. Department of Energy and its Alternative Fuels Data Center (U.S. DOE 2021; AFDC 2021). For China, we took federal subsidy amounts from Qian (2018) and the International Council on Clean Transportation (ICCT, 2017) and 2015 province-level subsidy amounts, including registration incentives, also from ICCT (2018), and assumed the latter to be the same from 2013 to 2017. We also included China's 10% vehicle tax exemption for PEVs (Argus 2020).

Figure 3d plots the average subsidy numbers for all the countries from 2010-2017. Denmark, Norway and China lead in the total amount of subsidies offered for PEVs. In Norway and Denmark, subsidies largely take the form of generous waivers of sales taxes; in China they mainly comprise combinations of federal, provincial, and registration incentives in vehicle ownership-restricted cities.

Figure 1. Evolution of sales-weighted average new vehicle fleet summary statistics for: (a) length, (b) width, (c) height and (d) wheelbase.

Source: KAPSARC analysis.

Note: mm=millimeter.

Summary Statistics

Figure 2. Evolution of sales-weighted average new vehicle fleet summary statistics for: (a) tailpipe- CO_2 , (b) MSRP, (c) curb weight, and (d) horsepower (hp).

Source: KAPSARC analysis.

Note: g/km=grams per kilometer; kg=kilograms.

Figure 3. Evolution of market share for: (a) PEV, (b) BEV, (c) PHEV, and (d) average subsidy.

Source: KAPSARC analysis.

Methodology

To estimate the tailpipe-CO₂ emissions of the counterfactual vehicle fleet in the absence of PEV subsidies, we assume that a PEV buyer would have bought the average ICEV of the same body type as the PEV. While simplistic versions of this counterfactual vehicle assumption have been utilized extensively in the literature (Holland et al. 2016; Archsmith, Kendall, and Rapson 2015; Graff Zivin, Kotchen, and Mansur 2014; Sheldon and Dua 2018), it does limit precise estimation of the tailpipe-CO₂ savings. Alternative approaches include choice-model-based counterfactuals (Xing, Leard, and Li 2019; Sheldon and Dua 2018). Indeed, our own previous research suggests that detailed choice-model-based counterfactuals do allow for a more precise estimation of the fuel savings (equivalent to CO₂ savings) (Sheldon and Dua 2018). However, given that this work aims to provide rough trend estimates by analyzing countries with varying market share penetrations, we chose to utilize the conventional counterfactual vehicle assumption.

As highlighted below in the results section, the scale of CO₂ savings dwarfs the variations related to the counterfactual vehicle assumption. Furthermore, recent research incorporating

alternative counterfactuals suggests that PEVs tend to displace higher efficiency vehicles (Xing, Leard, and Li 2019; Muehlegger and Rapson 2020). Thus, our tailpipe-CO₂ emissions reductions, and in turn, the related costs per tonne, represent optimistic estimates. Finally, we note that the cost per *additional* tonne of tailpipe-CO₂ avoided (as discussed later in this methodology section) incorporates information on the elasticity of PEV market share with respect to PEV subsidy from the literature as estimated using panel data regression.

We calculate the sales-weighted average characteristics for both the actual and counterfactual fleets as well as their respective components. More specifically, we calculate the fleet tailpipe-CO₂ average emissions for the new vehicle fleet including PEVs.⁷ Next, we replace the PEVs in the new vehicle fleet using the conventional counterfactual approach. Then, we calculate the fleet tailpipe-CO₂ average for this counterfactual fleet.

Next, we calculate the percentage of tailpipe-CO₂ emissions reduction in the new vehicle fleet using equation 1 as follows:

$$\% \text{ change in fleet CO}_2 = 100 * \frac{\text{Fleet CO}_2^{\text{Counterfactual Fleet}} - \text{Fleet CO}_2^{\text{Actual Fleet}}}{\text{Fleet CO}_2^{\text{Actual Fleet}}} \quad (1)$$

$$\Delta = \frac{(\text{Fleet CO}_2^{\text{non-PEV Fleet}} + \text{Fleet CO}_2^{\text{Replaced Fleet}} - \text{Fleet CO}_2^{\text{non-PEV Fleet}} - \text{Fleet CO}_2^{\text{PEV Fleet}})}{(\text{Fleet CO}_2^{\text{non-PEV Fleet}} + \text{Fleet CO}_2^{\text{PEV Fleet}})} \quad (2)$$

$$\Delta = \frac{(\text{Fleet CO}_2^{\text{Replaced Fleet}} - \text{Fleet CO}_2^{\text{PEV Fleet}})}{(\text{Fleet CO}_2^{\text{non-PEV Fleet}} + \text{Fleet CO}_2^{\text{PEV Fleet}})} \quad (3)$$

$$\Delta = \frac{N^{\text{PEV}} * (\overline{\text{Fleet CO}_2^{\text{Replaced Fleet}}} - \overline{\text{Fleet CO}_2^{\text{PEV Fleet}}})}{N^{\text{Total}} * ((1 - x^{\text{PEV}}) * \overline{\text{Fleet CO}_2^{\text{non-PEV Fleet}}} + x^{\text{PEV}} * \overline{\text{Fleet CO}_2^{\text{PEV Fleet}}})} \quad (4)$$

$$\Delta = \frac{x^{PEV} * (\overline{Fleet CO_2}^{Replaced Fleet} - \overline{Fleet CO_2}^{PEV Fleet})}{((1 - x^{PEV}) * \overline{Fleet CO_2}^{non-PEV Fleet} + x^{PEV} * \overline{Fleet CO_2}^{PEV Fleet})} \quad (5)$$

$$\Delta = \frac{x^{PEV} (\overline{Fleet CO_2}^{Replaced Fleet} / \overline{Fleet CO_2}^{non-PEV Fleet} - \overline{Fleet CO_2}^{PEV Fleet} / \overline{Fleet CO_2}^{non-PEV Fleet})}{((1 - x^{PEV}) + x^{PEV} * \overline{Fleet CO_2}^{PEV Fleet} / \overline{Fleet CO_2}^{non-PEV Fleet})} \quad (6)$$

where

Δ represents the percentage of tailpipe-CO₂ avoided,

$\overline{Fleet CO_2}^{Replaced Fleet}$ represents the sales-weighted average fleet tailpipe-CO₂ level (g/km) for the replaced fleet,

$\overline{Fleet CO_2}^{PEV Fleet}$ represents the sales-weighted average fleet tailpipe-CO₂ level (g/km) for the PEV fleet,

$\overline{Fleet CO_2}^{non-PEV Fleet}$ represents the sales-weighted average fleet tailpipe-CO₂ level (g/km) for the non-PEV fleet,

x^{PEV} represents the market share of PEVs in the new vehicle fleet,

N^{PEV} represents the total number of PEVs in the new vehicle fleet, and

N^{Total} represents the total number of vehicles in the new fleet.

Finally, using equation 7, we estimate the cost per tonne of tailpipe-CO₂ avoided by dividing the total subsidy cost by the total tailpipe-CO₂ avoided over the lifetime of the vehicle:⁸

$$$/tonne = \frac{N^{PEV} * \overline{Subsidy}^{PEV}}{N^{PEV} * (\overline{Fleet CO_2}^{Replaced Fleet} - \overline{Fleet CO_2}^{PEV Fleet}) * Vehicle Life * Annual Mileage} \quad (7)$$

$$$/tonne = \frac{\overline{Subsidy}^{PEV}}{(\overline{Fleet CO_2}^{Replaced Fleet} - \overline{Fleet CO_2}^{PEV Fleet}) * Vehicle Life * Annual Mileage} \quad (8)$$

$$Subsidy (\%) = 100 * \frac{\overline{Subsidy}^{PEV}}{(MSRP + Tax)^{PEV}} \quad (9)$$

Methodology

where

$\$/tonne$ represents the \$/tonne of tailpipe-CO₂ avoided,

$\overline{Subsidy}^{PEV}$ represents the sales-weighted average subsidy amount per PEV,

$\overline{Fleet\ CO_2}^{Replaced\ Fleet}$ represents the sales-weighted average fleet tailpipe-CO₂ level (g/km) for the replaced fleet,

$\overline{Fleet\ CO_2}^{PEV\ Fleet}$ represents the sales-weighted average fleet tailpipe-CO₂ level (g/km) for the PEV fleet,

$Subsidy\ (\%)$ represents the subsidy percentage on electric vehicles,

$MSRP$ represents the maximum suggested retail price for the vehicle and Tax represents the overall tax applied on the vehicle.

To calculate the cost per tonne of additional tailpipe-CO₂ avoided, we combine equation 8 with the extent of electric vehicle sales induced by the subsidy, i.e., elasticity of PEV market share with respect to PEV subsidy. This is done by dividing equation 8 by the elasticity of PEV market share with respect to PEV subsidy as shown in equation 10:

$$\$/additional\ tonne = \frac{\$/tonne}{\eta_{Subsidy}^{PEV}} \quad (10)$$

where

$\eta_{Subsidy}^{PEV}$ represents elasticity of PEV market share with respect to PEV subsidy.

For Europe, we calculate the elasticity of PEV market share with respect to PEV subsidy using the point estimates for the effect of incentives from Münzel et al. (2019). Their study estimates

that an incentive of 1,000 euros (EUR) increases PEV sales by about 5–7% on average, all else being equal — equivalent to a 13.07% average rise in the sales-weighted average subsidy of EUR 7,650 for the European countries considered in this analysis. Thus, the elasticity of change in PEV market share to change in subsidy is 0.459 (6% ÷ 13.07%). For the U.S., we use an average elasticity of PEV market share with respect to PEV subsidy of 0.4 taken from Li et al. (2017). Given the lack of literature on the variation of this elasticity with PEV market share, we assume these respective single point estimates for Europe and the U.S. stay constant over the spectrum of PEV market share considered in our analysis. Although the single point estimates for Europe, where the market share has varied the most, draw on data for the entire 2010-2017 time period, this is still a limiting assumption because from a policy perspective, the effectiveness of subsidies in inducing additional sales is expected to decrease with increasing PEV market share. The policy expectation is that the PEV market will reach an inflection point and become self-sustaining in its growth, beyond which the subsidies could be discontinued without any significant impact on the market (Jenn et al. 2020). For China, no such estimates for elasticity of PEV market share with respect to the combined PEV subsidies are available in the literature; therefore, we excluded China from this part of the analysis.

Figure 4 shows the ratio of the average new vehicle fleet characteristics for the PEV fleet and the replaced fleet; both are normalized by the entire non-PEV fleet. The vehicle dimensions considered include length, width, height, and wheelbase. The closeness of the ratios for the PEV fleet and the replaced fleet to the 45-degree line is reflective of the body-type equivalence assumption in our counterfactual approach. In other words, Figure 4

highlights that the characteristics of the actual PEV fleet are very similar to the replaced fleet

characteristics, as expected based on our conventional counterfactual approach.

Figure 4. Ratio of average new vehicle fleet dimensions for PEV fleet (y-axis) and replaced fleet (x-axis); both are normalized by non-PEV fleet for: (a) length, (b) width, (c) height and (d) wheelbase.

Source: KAPSARC analysis.

Note: The size of each country's bubble is proportional to its market share of electric vehicles in new vehicle sales corresponding to each year 2010-2017. The largest bubble size represents a market share of ~38%.

Figure 5 shows the same ratio for average (a) tailpipe- CO_2 , (b) price, (c) curb weight and (d) power. We note three important findings. First, the PEV fleet has significantly lower (near-zero) tailpipe- CO_2 emissions compared with both the non-PEV fleet as well as the replaced fleet. This is because the PEV fleet in most countries is dominated by BEVs that have zero-tailpipe emissions. Second, the tailpipe- CO_2 fleet average ratio for the replaced fleet is less than or close to 1 for most countries, meaning that it is more efficient than the average non-PEV fleet. Third, the PEV fleet has lower tailpipe- CO_2 emissions than the replaced fleet, as indicated by the datapoints falling well below the 45-degree line.

Most of the trends seen above for tailpipe- CO_2 emissions for the PEV fleet reverse for MSRP, curb weight, and power. First, the PEV fleet tends to have a higher fleet average for each of these three metrics than the average non-PEV fleet does. This is demonstrated by the fact that the ratio of PEV fleet to non-PEV fleet values (y-axis) is greater than 1 for most countries. Second, the fleet average MSRP, curb weight, and power for the PEV fleet tends to be higher than the replaced fleet. This is signified by the fact the data lies above the 45-degree line. On the other hand, the replaced fleet has similar or slightly lower MSRP, curb weight and power than the average non-PEV fleet for most countries other than the Netherlands. This is highlighted by the fact that the ratio of replaced fleet to non-PEV fleet (x-axis) is below 1 for most countries.

Figure 6 shows the variation in the percentage of tailpipe- CO_2 emissions reduction in the new vehicle fleet. We note four important observations.

First, in 2017, the total tailpipe- CO_2 avoided due to PEV adoption in these 11 countries was 5.63 million tonnes (0.51% in relative terms).⁹ For context, Bayer

and Aklin (2020) estimated that the European Union emissions trading system, the largest carbon market in the world, reduced emissions by a cumulative 1.2 billion metric tonnes between 2008 and 2016, an average of 133 million metric tonnes per year.

Second, the U.S. saw the highest tailpipe- CO_2 savings, followed by China. This is expected given that these are the top two markets in terms of overall sales. Moreover, since the U.S. fleet tends to be the dirtiest and most heavily driven, it also achieves the highest expected tailpipe- CO_2 savings from switching to PEVs.

Third, we find that the percentage of tailpipe- CO_2 avoided through PEV substitution varies linearly with PEV market share.

Fourth, the calculated tailpipe- CO_2 emissions reduction percentage closely follows the special case curve.¹⁰ It is worth noting that on a relative percentage basis, the percentage values differ significantly from the special case curve even at low market shares as shown in Figure 6b. However, given the low percentage values, the extent of percentage difference from the special case curve is almost inconsequential. Two factors contribute to larger negative variation from the special case curve — first, a higher proportion of PHEVs in a country's PEV mix leads to non-zero $\overline{Fleet\ CO_2}^{PEV\ Fleet}$ in equation 9 and thus lower $\eta_{PEV}^{CO_2}$ values, and second, the replaced non-PEV fleet on average being cleaner compared with the entire non-PEV fleet, i.e., countries with a lower ratio of $\overline{Fleet\ CO_2}^{Replaced\ Fleet} / \overline{Fleet\ CO_2}^{non-PEV\ Fleet}$ or where PEVs tend to replace relatively cleaner vehicles.

Figure 5. Ratio of average new vehicle fleet characteristics for PEV fleet (y-axis) and replaced fleet (x-axis); both are normalized by non-PEV fleet for: (a) tailpipe- CO_2 , (b) maximum suggested retail price (MSRP), (c) curb weight and (d) power.

Source: KAPSARC analysis.

Note: The size of each country's bubble is proportional to its market share of electric vehicles in new vehicle sales corresponding to each year 2010-2017. The largest bubble size represents a market share of ~38%.

Methodology

Figure 6. Variation in (a) cumulative tailpipe- CO_2 avoided (y-axis) with time, (b) percentage of tailpipe- CO_2 avoided (y-axis), and (c) percentage variation from the special case curve (y-axis), with respect to the electric vehicle market share (x-axis).

Source: KAPSARC analysis.

Figure 7 shows the variation in the cost per tonne with subsidy percentage for PEVs for the different countries. We note three points of interest here. First, the cost per tonne varies almost linearly with

subsidy percentage for PEVs. This is in line with expectation, as high subsidy percentage means high subsidy costs.

Second, the cost (on PPP basis in 2010 US\$) per tonne of tailpipe- CO_2 avoided can be as high as US\$1,600 with a PEV sales-weighted average value of US\$739. This is more than an order of magnitude higher than the social cost of carbon (Rennert and Kingdon 2019), which we attribute to both the high subsidy amounts per PEV as well as the low extent of tailpipe- CO_2 avoided. Note that the cost per tonne of CO_2 avoided would be higher than our conservative estimate for three reasons. First, we are only considering tailpipe- CO_2 emissions. Second, conventional counterfactuals overestimate tailpipe- CO_2 avoided compared with choice-model-based counterfactuals that suggest PEVs tend to displace higher-efficiency vehicles (Xing, Leard, and Li 2019). Lastly, we assume that the elasticity of PEV market share with respect to PEV subsidy is equal to 1. The cost estimate would

become even higher if the actual extent of electric vehicle sales induced by the subsidy (versus sales that would have occurred even without the subsidy), i.e., elasticity of PEV market share with respect to PEV subsidy, were considered.

Third, on a PPP basis, the cost per tonne is highest for China followed by Denmark and Norway. In other words, China is spending more on subsidizing tailpipe- CO_2 emissions reduction through PEV deployment than the U.S. or Europe. It is worth noting though that for China, vehicle electrification is as much an industrial policy to help it leapfrog other countries in the PEV manufacturing space as it is a tool to help reduce tailpipe- CO_2 emissions and local air pollution. This to some extent highlights the reasoning behind China's aggressive subsidy policies.

Figure 7. Variation in subsidy cost per tonne of tailpipe- CO_2 avoided (y-axis) with subsidy percentage on electric vehicles (x-axis).

Source: KAPSARC analysis.

Note: The size of each country's bubble is proportional to its market share of electric vehicles in new vehicle sales corresponding to each year 2010-2017. The largest bubble size represents a market share of ~38%.

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Finally, using equation 13, we combine the results from Figure 7 with the extent of electric vehicle sales induced by subsidies to obtain the cost per tonne of additional tailpipe-CO₂ avoided. Combining the results for Europe and the U.S., we get a PEV sales-weighted average cost of US\$701 per *additional* tonne of tailpipe-CO₂ avoided (on PPP basis in 2010 US\$). This contrasts with the average

across Europe and the U.S. of US\$309 per tonne of tailpipe-CO₂ avoided (on PPP basis in 2010\$).¹¹ Thus, due to the fact that the elasticity of PEV market share with respect to PEV subsidy is less than half (the majority are allocated to consumers who would have purchased the PEV regardless), the cost per tonne of emissions avoided more than doubles.

Conclusion and Policy Implications

We find that PEV adoption subsidies are an expensive way to reduce tailpipe-CO₂ emissions, costing more than an order of magnitude more than the social cost of carbon. This warrants research into, and adoption of, innovative subsidy designs with higher cost-effectiveness as well as alternative approaches and technologies, including on-board mobile CO₂ capture systems (Aramco 2021). The issue of PEV subsidies is especially critical under current circumstances when governments are allocating billions of dollars to promote clean vehicle sales as part of COVID-19 economic stimulus packages (CNN Business 2020; Financial Times 2020a, 2020b, 2020c; AVERE 2020; Reuters 2020; Caixin 2020). To improve the impact and cost-effectiveness of such policies, policymakers could opt for more targeted subsidy designs, one of the “three T” principles — “timely, temporary, and targeted” — for designing an effective stimulus package (Elmendorf and Furman 2008; Bordoff 2020). Our previous research suggests that targeted subsidy designs based on consumer income can double PEV subsidy policy cost-effectiveness (Sheldon and Dua 2019b, 2020). Real world pilot tests involving targeted subsidy designs for vehicle retirement and replacement have also proven more cost-effective in inducing additional PEV sales (Sheldon and Dua 2019a).

Another noteworthy policy implication involves countries that began offering subsidies for PEV deployment relatively late, such as Germany, which started in 2016 — and with lower subsidy

per PEV than most other countries, at that. Such late-movers likely benefit from earlier cycles of subsidization offered by other countries in their own markets, which not only increased local demand, but helped the global PEV and battery industries to fund research, develop economies of scale, and increase efficiency over time. Reduced PEV and battery manufacturing costs could also help reduce the threshold for PEV subsidies to be effective in the late entrant countries.

The solar photovoltaic (PV) industry offers a proven model in this regard: research suggests that a subsidy for PV in one country assists in increasing the adoption elsewhere because it boosts investment in innovation by international firms (Gerarden 2017). Gillingham and Stock (2018) argue that German solar PV consumer subsidies have in turn subsidized lower-cost solar for the rest of the world. It is worth noting that Germany was among the first countries to lead in solar PV manufacturing and deployment through its generous local deployment subsidies (Quitow 2015). However, Germany’s early mover advantage in the PV manufacturing space did not pan out as expected once China (a late entrant) flooded the global PV market with products that build on the initial technology leaps made by Germany (and others) and the higher consumer subsidies that helped fuel them (Quitow 2015). Given Germany’s experience in the PV sector and its extensive expertise in automobile manufacturing, it could be argued that German policymakers learned their lesson from the PV experience and have more strategically played the waiting game in subsidizing local PEV manufacturing and deployment.

Endnotes

1 Hydrogen fuel cell electric vehicles have been clubbed with pure battery electric vehicles in this analysis because of (i) very limited sales of hydrogen fuel cell electric vehicles during the time period considered in this analysis, (ii) similar subsidies offered for both, and (iii) both having zero tailpipe-CO₂ emissions.

2 Accounting for emissions associated with manufacturing of vehicle components and vehicle assembly together with upstream and tailpipe emissions would enable the assessment of life cycle emissions. However, due to the lack of model-level information pertaining to manufacturing-related emissions, this work focuses on tailpipe emissions only.

3 Japan is the only country that has recently included upstream GHG emissions standards, in new 2030 light-duty vehicle regulations (ICCT 2019).

4 The analysis period is limited to 2017 because of the lack of literature on subsidies in European countries in 2018 and 2019. Moreover, given that the dataset covers a broad range of PEV market shares ranging from almost 0 to 38% by covering different markets, expanding the analysis to 2018 and 2019 would be unlikely to impact our findings.

5 Low fuel taxes in the U.S. versus high fuel taxes and registration taxes (based on vehicle CO₂ emissions) in Europe likely play a significant role.

6 The relatively higher market share of luxury electric vehicles as well plug-in hybrid electric vehicles in the U.S. and Europe and lack thereof in China likely help explain this.

7 For PHEVs, a utility factor of 0.5 is assumed for calculating the combined tailpipe-CO₂ emissions (mean of tailpipe-CO₂ emissions in electric mode and internal combustion engine mode).

8 The annual mileages in Europe, the U.S. and China were assumed to be 9,072 miles (Ricardo-AEA 2014), 11,500 miles (FHWA 2019) and 8,787 miles (Sheldon and Dua 2020), respectively. The vehicle lives in Europe, the U.S. and China were assumed to be 15 years (Ricardo-AEA 2014), 16 years (Davis, Diegel, and Boundy 2013) and 14.5 years (Hao et al. 2011), respectively.

9 The cumulative tailpipe-CO₂ numbers are based on the assumption that all of the new vehicles sold since 2010 are still running on the road in 2017, in line with the average vehicle life assumption for all 11 countries.

10 For the special case corresponding to: (i) Only BEVs in the PEV fleet, i.e., $\overline{Fleet CO_2}^{PEV Fleet} = 0$ and (ii) replaced fleet corresponding to the average non-PEV fleet, i.e., $\overline{Fleet CO_2}^{Replaced Fleet} = \overline{Fleet CO_2}^{non-PEV Fleet}$; by substituting these values in equation 9, we get $\eta_{PEV}^{CO_2} = x^{PEV} / (1 - x^{PEV})$. In other words, the elasticity is equal to the ratio of market share of PEVs to market share on non-PEVs. The dashed curve in Figure 6a corresponds to this special case.

11 Our findings from the detailed conventional counterfactual assumption appear to be in line with those from the choice model-based counterfactual measured for the case of the U.S., for which model-level subsidy information was available (unlike for Europe). For 2017 data, applying a choice model-based counterfactual resulted in a cost of US\$3.2 per additional gallon of gasoline saved (Tamara L. Sheldon, Omar Al Harbi, and Dua 2020). Using GHG equivalence factors from the EPA (2019), this translates to US\$447 per additional tonne of tailpipe-CO₂ avoided, in 2010 US\$. The corresponding value based on the detailed conventional counterfactual assumption used in this paper is US\$438 per additional tonne of tailpipe-CO₂ avoided (in 2010 US\$).

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Appendix

Figure A1. Evolution of sales-weighted average new plug-in electric vehicle (PEV) fleet summary statistics for: (a) length, (b) width, (c) height, and (d) wheelbase.

Source: KAPSARC analysis.

Note: mm=millimeter.

Appendix

Figure A2. Evolution of sales-weighted average new PEV fleet summary statistics for: (a) tailpipe carbon dioxide (CO₂) emissions, (b) manufacturer's suggested retail price (MSRP), (c) curb weight, and (d) horsepower (hp).

Source: KAPSARC analysis.

Note: g/km=grams per kilometer; US\$=United States dollars; kg=kilograms.

Figure A3. Evolution of the ratio of sales-weighted average new vehicle fleet summary statistics for PEV fleet divided by the overall fleet for: (a) length, (b) width, (c) height, and (d) wheelbase.

Source: KAPSARC analysis.

Note: mm=millimeter.

Appendix

Figure A4. Evolution of the ratio of sales-weighted average new vehicle fleet summary statistics for PEV fleet divided by the overall fleet for: (a) tailpipe- CO_2 emissions, (b) MSRP, (c) curb weight, and (d) hp.

Source: KAPSARC analysis.

Note: g/km=grams per kilometer; US\$=United States dollars; kg=kilograms.

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About the Project

Promoting the adoption of energy-efficient vehicles has become a key policy imperative in both developed and developing countries. Understanding the impact of various factors on adoption rates of energy-efficient vehicles forms the backbone of KAPSARC's research into light-duty vehicle demand. These factors include (i) consumer-related factors – demographics, behavior, and psychographics; (ii) regulatory factors – policies, incentives, rebates, and perks; and (iii) geo-temporal factors – weather, infrastructure, and network effects. Our team is currently developing models at different levels: micro-level models using large-scale data comprising new car buyers' profiles, and macro-level models using aggregated adoption data to understand and project the various factors that affect the adoption rate of energy-efficient vehicles.

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