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The Case for Plug-in Hybrid EVs with Long All-Electric Range as a Long-term Solution and Policies to Support Them

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Executive Summary

While plug-in electric hybrid vehicles (PHEVs) are about 23% of global sales of battery EVs and PHEVs (27 million out of 118 million) [1], many consider PHEVs, including extended range EVs, a transition technology that phases out to enable an all BEV and fuel cell EV future. We make the case in this paper that a PHEV with more than 80 miles of real-world all-electric range (AER), based on USEPA range tests, is a long-term sustainable transportation solution along with battery EVs and fuel cell EVs, and not just a transition technology. With 68 long-range PHEVs emerging in recent years (none in the US) [2], policy makers globally have not had to consider how they are quite different than other PHEVs when creating zero-emission vehicle mandates, incentives, and other policies. We recommend nine supporting policies for countries, states, and provinces to treat them differently than short- and medium range PHEVs.

Keywords: National/Federal policies, State/Provincial/Regional policies, plug-in hybrid electric vehicles, light-duty vehicles, GHG reduction

1 The Case for PHEVs with Long-All-Electric Ranges (LR-PHEVs)

To date, the debate over the benefits of PHEVs compared to other options has focused on existing PHEVs outside of China which until very recently have been PHEVs with short or medium AERs (e.g., less than 39.9 miles or between 40 and 79.9 miles). We propose to shift and focus the debate to more completely consider the technology of long-range PHEVs. There is a stark difference between the performance and characteristics of a PHEV with 20 miles (32 km) AER, with 80 miles (129 km) AER and one with 200 miles (322 km) AER. This paper asserts that policy decisions should take account of the different AERs of PHEVs, treat long-range PHEVs differently than short-range ones, not get caught up in the media reports focusing on short-range PHEVs, or mistakenly apply findings on short range PHEVs in European company cars (mostly provided for free to employees) to other countries that don't have many company cars.

The primary policy recommendation of this paper is that current mandates and programs incentivizing automakers to sell 100% battery EVs (BEVs) and fuel cell EVs should be expanded long-term to include long-range PHEVs with more than 80 miles AER (inclusive of policies such as purchase rebates or tax credits). Under the current policy models for zero-emission vehicle (ZEV) sales mandates, all BEVs are treated equally (each register one compliance credit), even though each make and model have different environmental impacts, and the same is true for fuel cell EVs. For example, BEVs with a 150-mile range compared to one with a 450 -mile range are very different in terms of their environmental costs and benefits, but each register one compliance credit. The same logic applies to small, 3000-pound BEVs compared to very large 10,000-pound BEVs, and the same logic applies to BEVs with different battery chemistries such as Lithium Nickel Magnesium Cobalt (LiNMC) and sodium ion (NIB), where the greenhouse gas (GHG) emissions from mining and manufacturing emissions typically are very different. Under current ZEV mandate policy, they all earn one compliance credit.

Today, BEVs, fuel cell vehicles and long-range PHEVs all suffer from the lack of an international consensus on comprehensive cradle-to-grave analysis of GHG other environmental impacts that might be associated with battery chemistry, battery specific energy, vehicle size, aerodynamics and other factors. Some analyses, such as the GREET R&D model [3] and analysis for the European Commission [4] are getting close to this type of comprehensive analysis. Below we show that LR-PHEVs have lower GHG emissions from mining and battery manufacturing than a BEV equal to >11 percent of lifetime miles (maybe 20 percent) of a comparable gasoline vehicle, based on these and other analyses.

We also show below that when PHEVs use 85 percent ethanol and 15 percent gasoline (E-85), have stricter regulations on air pollutants from high-power, engine cold starts, and their smaller mining and battery manufacturing emissions are considered, a long-range PHEV is essentially equivalent environmentally to a long-range BEV and likely slightly better than a very long-range BEV. This is because long-range PHEVs plug in more often and drive 80 to 95% of miles on electricity from plugging in, but this needs to be verified as data becomes available and corrective actions taken by automakers if necessary to make up any missed GHG emissions. Long-range PHEVs need treated very similarly to BEVs and fuel cell EVs in policies for practical reasons too. The last year has shown how difficult it will be to reach the last 30 to 40 percent of the market of new car and truck buyers with policies only favoring BEVs and fuel cell EVs due to the rise in opposition and scepticism regarding these technologies. In the policy section below, we recommend several policies below for long-range PHEVs to make them eligible to be treated equally to BEVs and fuel cell EVs and preventing the policies from resulting in too many PHEVs.

1.1 Benefits of long-range PHEVs.

For this paper we define a light-duty PHEV with a long all-electric range (AER) as one with 80 miles or more using the USEPA method, and we estimated the USEPA window sticker range for all miles in this paper by adjusting the CTLC or WLTP all -electric range down by 35 or 22 percent, respectively [5]. In addition to the many drivers that want long-range PHEVs instead of battery EVs or fuel cell EVs, we base our case for PHEVs with long all-electric range on several factors in the sections below [6]. The advantages of light-duty, long-range PHEVs include [6, 2].

- A combined transportation electrification strategy inclusive of LR- PHEVs, BEVs and fuel cell EVs is a faster path for the world to adopt light-duty vehicles with extremely low GHG emissions. As mentioned above, the 27 million PHEVs and 91 million BEVs today in the world, illustrate that.
- LR-PHEV cars and trucks are a better solution (because they are dual fuel) to survive long-term catastrophes and daily emergencies (e.g., wildfires, earthquakes, windstorms, hurricanes, tsunamis, power outages, riots, vandalism, tornadoes, floods and public service power shutoffs) and can provide power export using the engine and/or the battery during these situations,
- LR-PHEV cars and trucks can support the grid and exert a downward pressure electricity on rates for all utility users with existing managed charging programs and upcoming bi-directional charging programs which pay the drivers for grid services,
- LR- PHEV cars and trucks are a better solution for personal EV drivers and commercial fleets that are renters and change residences or business locations relatively often. Because they can function well using level 1 and 2 charging, PHEVs decouple the purchase and cost of high-cost, high-rate charging infrastructure from the function of electrified transportation.

- LR- PHEV cars and trucks are a better solution for owners of used cars and trucks who are often low-income residents or commercial operators,
- LR- PHEV cars and trucks have much less cost impact to the grid. They have a lower demand charge part of their electricity bill and help mitigate scale-up concerns of building a network of away-from-home light-duty vehicle DC fast chargers and/or hydrogen infrastructure for light-duty vehicles,
- Drivers in rural areas often drive longer distances than others and in areas with little access to charging. As a result, long-range PHEVs are a better option for the portion of the world that covers small and mid-size towns where trip distances (when needed) exceed those in urban megacity regions,
- LR-PHEVs are a better option in regions for drivers who typically drive long trips and long annual distances,
- LR PHEV cars and trucks are particularly useful in cold weather regions and for fleets that need to tow trailers, boats, and campers,
- LR PHEV trucks are a better option for as the hub for a mobile emergency command and control center that can provide significant vehicle power export to support critical communications, lighting equipment, and portable battery recharging,
- LR-PHEVs are particularly suited to larger and more massive commercial vehicles due to their much smaller batteries (compared to battery EVs),
- Long-range PHEVs are attractive to late adopters and drivers who are sceptical of or opposed to battery EVs or fuel cell EVs. The electrification of these buyers' vehicles is comprehensively needed to electrify the last 30 to 40% of the market,
- LR-PHEVs can realize the same GHG reduction benefits of a comparable long-range BEV when considering battery mining and manufacturing emissions, E-85 fuels, active control of high-power cold start emissions, and other factors,
- LR-PHEV cars and trucks use substantially less critical minerals (due to their smaller batteries compared to battery EVs), and thus reduce pressure on the need to rapidly scale supply chains for these minerals and hedge against supply chain disruptions,
- LR- PHEV cars and trucks can weigh less than full function BEV cars and trucks, resulting in less upward pressure on vehicle sizes with significant cost and safety implications,
- LR- PHEV cars and trucks will have important long-term adopters globally regardless of their cost and many car and/or truck manufacturers will want to serve this market,
- LR- PHEV cars and trucks offer substantial air quality benefits that are very similar to BEVs.

1.2 Definition of PHEV.

As members of the policy committee of the Strong PHEV Coalition, we have traditionally defined a Strong PHEVs as those with over 50 miles of all-electric range posted on the US Environmental Protection Agency (USEPA) window sticker and that meets the additional strict requirements of the California Air Resources Board (CARB) Advanced Clean Cars II (ACCII) regulation which is on hold pending litigation. PHEV is a very broad term for a type of dual- or tri-fuel vehicle that includes series, parallel and power split designs with many possible all-electric ranges, powertrain energy management schemes, type of transmission (or none), type of liquid or gaseous fuel, charging technology or engine. However, they all must be able to plug into an outlet or charging station. EREV (extended range EV) is a marketing term for a type of PHEV that behaves consistently whether the engine is operating or not and typically provides a high AER. EREVs may or may not use a series-hybrid design [6].

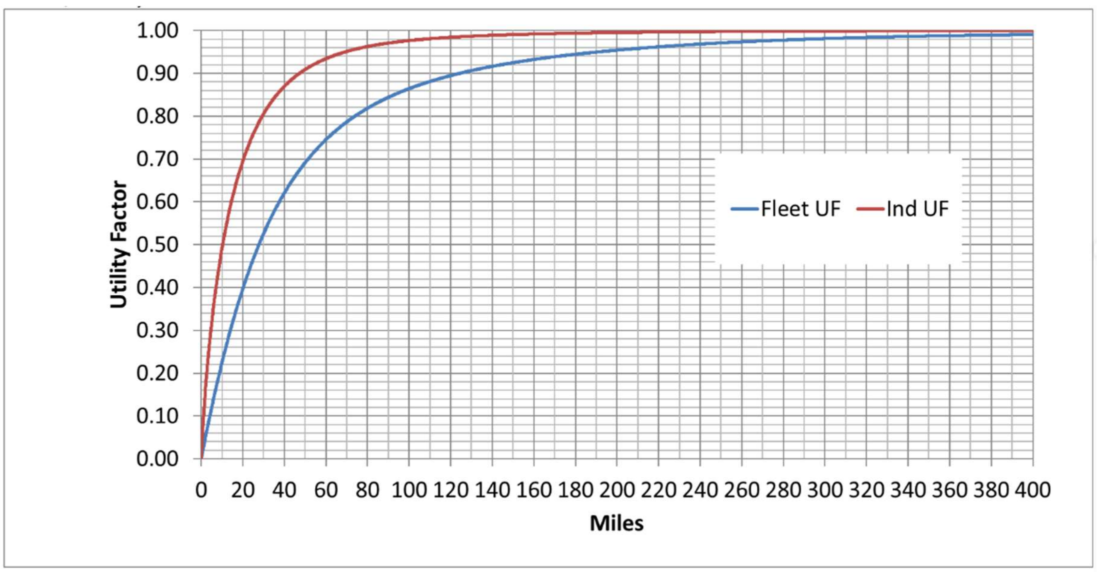
1.3 Dozens of long-range PHEV models exist outside of the US, but none in the US.

Our market research shows that PHEVs with over 80-mile AER already exist (or are pending near-term) with 68 makes and models available globally, but none are available in the US. There are 29 PHEVs available in China, Europe, and other countries outside of the US with over 120 miles estimated AER [2]. There are 12 PHEVs outside of the US with over 160 miles AER and 5 with over 200 miles AER [2]. Over 120 more medium range PHEVs (AER of between 40 to 79.9 miles) are available worldwide including seven existing or near-term pending in the US [2]. Typical brands for these long-range PHEVs include AITO, BYD, Changan, Chery, Denza, Dongfeng, Ford, GAC, Geely, GWM, IM Motors, Leapmotor, Li Auto, Lotus, Nissan, Renault, Smart, Volvo, Voyah, VW, Xpeng, and Zeeker [2]. They typically have both level 2 and DC fast charging and use either lithium iron phosphate (LFP), Li-NMC or hybrid Freevoy batteries with pack sizes between 18 and 50 kWh. The non-luxury models have prices between $15,000 and $45,000 USD with 40 models priced at less than $35,000 [2]. While most of the sales of the LR-PHEVs are in China, some are sold in the United Kingdom, European Union, Australia, Southeast Asia and a few other countries.

1.4 PHEVs with over 80-mile AER plug-in 80-95 percent of miles in the US.

With an 80-mile all-electric range PHEV, 80% of miles are electrified from plugging in. That percentage increases to 95% for a PHEV with 180- mile AER in the US (based on SAE International chart below), which is called a Utility Factor (UF) curve chart. The left and middle of this chart are based on SAEJ2841 data, while the right is extrapolated [8]. The lower line (Fleet UF) considers the condition that not all drivers will plug in frequently, while the upper line (Ind UF) shows the electric miles from plugging in as percentage of total miles from individuals who typically plug in.

For countries with long annual distances driven such the US, Canada and Australia, this chart is a good starting point to base policy but should be refined as more data for long- and very-long-range PHEVs becomes available. Each country should use a data-driven approach and develop their own definition of a long-range PHEV along with other factors discussed in the policy sections below. Recommendations to improve this chart are in sections 2.1, 2.4 and 2.8 below. Recent data from the US shows that PHEV drivers with all types of AERs do plug in, that PHEVs with longer AERs drive more of their annual miles electric than those with shorter AERs, and that long-range PHEVs are charged at a rate greater to or equal to the hypothetical maximum expressed in datasets such as SAE J2841 [6, 7].



Percent of Electric vs non-electric miles (Y-Axis or UF) for PHEVs with different all-electric ranges (X-axis or miles) is shown in the chart referencing SAE International [8].

1.5 Long-range PHEVs that use E-85 have even lower greenhouse gas emissions and flexibility.

When long-range PHEVs are offered as flex fuel vehicles that can use the best types of E-85, their GHG emissions can become comparable to a ZEV. For example, CARB finds E-85 on average to be 35 percent less GHG than reformulated gasoline. Some types of E-85 are 66 percent less GHG than reformulated gasoline in California [9]. Several states already have a large infrastructure for selling E-85. For example, California has 500 fuelling stations with E-85[6]. Other biofuels or e-fuels also have a similar potential as shown by the recent European Commission proposal to modify their current zero-emission vehicle regulation to allow limited amounts of biofuels and e-fuels in 2035 and later years for PHEVs to use [9].

1.6 Considering the mining and battery manufacturing and the factors above makes the total GHGs of LR-PHEVs equivalent to that of battery EVs with 400-mile ranges.

Current zero-emission vehicle mandate policies often don't consider the impact of mining and manufacturing batteries when comparing battery EVs to PHEVs, instead they primarily consider the tailpipe GHG and other air pollutants. However, when the mining and manufacturing GHG emissions are considered along with the factors above (sections 1.4 and 1.5) long-range PHEVs have essentially the same environmental benefits as BEVs with 400-mile ranges and better than BEVs with 450-mile ranges. Similarly, aerodynamic, long-range PHEV sedans can have less environmental impact than battery electric large SUVs, pick-ups and vans.

The research on the emissions from mining and battery manufacturing is nascent but rapidly improving especially with the European Union requirements for battery passports [10]. Leaders in studying mining and battery manufacturing emissions for BEVs and PHEVs include University of California, Davis [11], Argonne National Laboratory [3], European Union [4], University of Michigan [12], Circular Energy Storage Research and Consulting [13], Swedish Energy Agency [14], and the International Council on Clean Transportation [15].

Assuming a 140,000 mile life and a usable pack size that is about one-fifth the size of a comparable BEV, a LR-PHEV has to drive about 4,000 miles to payback its battery GHG emissions, while a comparable BEV has to drive about 20,000 miles, resulting in a net benefit of about 16,000 miles or 11.4% of lifetime miles of a gasoline vehicle [16, 12]. Add this with the benefits in Sections 1.1, 1.4 and 1.5 and that results in an equivalence between a BEV and a LR-PHEV. Considering a more extreme case, using the European Union life cycle analysis data [4] and comparing a LR-PHEV with a 20-kWh pack with a 450-mile range BEV with a 140-kWh pack (usable), the net benefit is about 16% of lifetime miles of a gasoline vehicle. Note that a worse case is a 200-kWh pack (total) in a Chevy Silverado pick-up. Usable pack sizes of 110 to 140 kWh are now found in some Chinese and European BEVs, and according to McKinsey and Company [17] a 140-kWh usable pack would equal 13 tons of CO2 or about 32,500 miles (23% of lifetime miles) and a net benefit of 20% of lifetime miles of a gasoline vehicle [18]. These comparisons while different, illustrate the environmental benefit of smaller packs in LR-PHEVs compared to BEVs and show the need for a better consensus on these upstream emissions. These observations are formed into policy recommendations in section 2.6.

One report shows fuel cell EVs using renewable and natural gas as feedstocks for hydrogen fuel having very different life cycle analysis GHG emissions [15] and the GREET R&D model shows them much lower than BEVs [3, 16]. However, for practical reasons mentioned earlier, zero-emission mandates today allow fuel cell EVs to qualify as zero grams per mile GHG (tailpipe emissions only) and earn one compliance credit (see section 2.7), even though life-cycle analysis shows a wide range of GHG lifetime emissions between the different types of fuel cell EVs. Similarly, BEVs have this same issue and policy treatment. This same logic should apply to long-range PHEVs as we detail in policy sections 2.2, 2.7 and 2.8 below.

1.7 What about other pollutants from the engine?

In general, the best gasoline spark-ignited engines and fuel systems have become very low emission for NOx, ROG, PM, CO and other non-GHG pollutants due to a 65-year effort by CARB and other regulators. The best PHEVs have improved to address air pollution concerns that were aimed at earlier generations of PHEVs. For example, CARB made the ACCII regulation much stricter for traditional pollutants based on best-in-class PHEV technology including methods to address high-power engine cold start emissions [19].

As a result, the traditional and GHG emissions from long-range PHEVs come close to, and in some cases improve on, the emissions of a long-range battery EV when factors in the sections above are combined.

2. Policies to Support Long-range PHEVs

While many policies today are discouraging the manufacture and adoption of PHEVs, we propose here a set of policies that can be used to define incentives and regulations in California, US, Canada, United Kingdom (UK), Europe, Australia and other countries to encourage PHEVs with long- or very-long all-electric ranges. Each jurisdiction can choose to define the minimum AER for long-range PHEVs. In general policies for long-range (80-to-119.9-mile AER) PHEVs and very-long-range PHEVs (120 miles and above AER) should be very similar to policies for BEVs and fuel cell EVs based on the above analysis and very different than policies for short- and medium-range PHEVs (79.9 miles or less AER). This paper is not defending or proposing policies for short-range PHEVs, due to their higher environmental costs than comparable technologies.

2.1 Require more consumer information and incentivize plugging in.

First, regulators should create regulations requiring education of BEV and PHEV owners and operators by automakers which would include the need to plug in PHEVs. For example, automakers should place QR codes on the car door sill and charge port that direct one to government websites that provide extensive information about the vehicle including battery type, charging types, options and speeds, AER under various conditions, cost of charging by zip code and so on [6]. Keeping the website up to date could be done by government, non-profits or possibly crowd sourced. Further, automakers should be required to have a least two types of reminders for PHEV drivers to plug in such as dashboard visual or audio reminders, games, tips and rewards along with information on the cost savings from home charging. In addition, automakers should be required to display a PHEV's percentage of electric miles vs total miles to the driver and how that compares with other drivers on dashboard display. Battery passports and battery state-of-health information should also be provided to help resale value and recycling. Additional ideas are available in this reference [6].

2.2 Reform PHEV purchase incentives.

Second, policy makers should include long-range and very-long-range PHEVs in financial incentive programs for consumers (tax credits and rebates), so they earn the same incentive as BEVs and fuel cell EVs. Today, incentive programs typically do not incentivize PHEVs or reward them at half the value. For example, in Canada, PHEVs receive half the incentive of BEVs [20]. This approach of providing half incentives may be appropriate for short- and medium range PHEVs, but not for long- and very-long-range PHEVs based on the analysis above. Alternatively, a more graduated incentive could be used where very-long-range PHEVs receive the most; equivalent to BEVs, and long-, medium- and short-range PHEVs receive proportionately less as their AER decreases.

2.3 Reform CARB's Advanced Clean Cars II.

Currently CARB is developing a new regulation for light-duty vehicles, called the Drive Forward Light-Duty Vehicle Program that would potentially replace CARB's Advanced Clean Cars II, if California's litigation to keep ACC II is unsuccessful [21]. We recommend that CARB's new regulation should treat PHEVs with 120 or more miles of all-electric range (based on USEPA window sticker) the same as BEVs and fuel cell EVs (same credits for all three types), allow individual automakers to make up to 50% of their zero-emission vehicle compliance with PHEVs with 80 miles or more AER but keep the current 20% cap on automaker's PHEVs with 50 or more AER. The above approach is very similar to ACC II which limits an automaker to 20 percent of their zero-emission vehicle sales as PHEVs with 50 or more miles AER (USEPA window sticker) [22]. In addition, CARB should require E-85 flex fuel capability in PHEVs, require bidirectional charging in PHEVs with 120 miles or more AER and incentivize wireless charging of long-range PHEVs.[6] Requirements for best-in-class control of emissions from high-power cold starts and other emission controls similar to ACC II should be required [23]. Making these changes will not result in large numbers of PHEVs outcompeting BEVs because of the 20% and 50% caps recommended above and because many automakers do not and will not manufacture long-range PHEVs [6].

2.4 Require automakers and governments to provide more data to understand UF curves.

Regulators should require light-duty automakers to provide data to environmental regulators in each country or state who implement zero-emission vehicle mandates regarding how many miles their PHEVs operate on using off-board electricity compared to total miles (i.e., UF curves) in order to improve policies. Similarly, regulators should require other government sources of data on this topic to provide these regulators, e.g., smog check data, or road-use fee data. UF curves are only as good as the data behind them. The EU's regulation 2021/392 requires all new cars to have on-board fuel consumption monitoring which collects real-world fuel and electricity consumption data for regulators [24]. Data provided to regulators and AER test methods should clearly define the proportion of miles covered only by off-board electricity, which may be a challenge for some PHEVs that allow engine turn-ons more frequently compared to those that do not.

2.5 Update the Utility Factor (UF) curves and GHG emissions from E-85 for each country every few years.

Each country has different average annual miles travelled and this diversity of operations leads to a diversity of UF curves. For example, long- range PHEVs will have a greater percentage of all-electric miles in a country with relatively low total average annual miles travelled compared to one with twice as many (e.g., 6,000 vs 12,000 miles). Updating of the operational performance of PHEV makes and models and UF curves should be performed when smog check, road-use fee, and automaker-provided data shows new data for existing PHEVs. For example, in Europe in 2023, seventy-seven percent of new PHEVs are corporate cars [25]. In general, for new passenger cars (Oct. – Nov 2025 data), corporate cars are 58 percent of total sales (company cars, which are mostly provided for free to employees to take home are 37 percent of sales, car dealers and manufacturers (15%), and short-term rentals (6%) [26]. Company cars provided to employees have a very different UF curve as they have no reason (and probably no equipment) to charge at home at night. Historically, national tax policies in many EU countries encourage companies to provide PHEVs to employees to take home and free charge cards to pay for gasoline, but no incentive to use electricity to charge [27].

Because of this issue, the European Union should develop two UF curves one for company-owned PHEVs provided to employees and one for PHEVs owned by individuals and fleets [28]. Because company-owned PHEVs provided to employees to charge at home are so common, combining the data for both types of PHEVs provides highly misleading data for policy makers. In addition, long-term policy should focus on what is appropriate for long- and very-long range PHEVs, but they have not been adequately considered by past studies.

For long-range PHEVs, UF curves should go out to a least a PHEV with 200 miles AER which requires extrapolation of data from PHEVs with shorter all-electric ranges (see chart above). However, as soon as robust data becomes available for these longer-range PHEVs, the UF curve should be updated on an on-going basis. Securing this robust and useable data for PHEVs has proven difficult to date [6]. Examples of issues with using smog check data in California to update the UF curve include difficulty in analysing extremely scattered data, lack of data from new PHEVs and long-range PHEVs, and improper use of averaging.

The GHG emissions in grams per megajoule (well-to-wheel) for E-85 or other allowed biofuels should be updated every few years by each country that allows them to be used in PHEVs and that has sufficient infrastructure to sell E-85. In addition, countries or states may want to not allow E-85 with relatively high GHG to be sold as today's ethanol can vary from 22 to 78 grams per megajoule [9].

2.6 Fund an international effort to reach consensus on mining, recycling, and battery manufacturing emissions for PHEVs and BEVs and make policy recommendations.

Fund a broader collaborative effort by Europeans, US and other researchers to reach consensus on the mining, recycling and battery manufacturing emissions from many types of mines and batteries so that BEVs (150-500 miles AER) and PHEVs (20 to 200 miles AER) can be compared and policies improved using improved cradle-to-grave life-cycle analysis data. At minimum, LFP, Li-NMC, lithium metal oxide (LMO), hybrid Freevoy, solid state batteries (SSB), and sodium ion batteries (NIB) should be included in this consensus effort. Specific policy recommendations may not be clear at this time, but policy ideas should be examined in this study. At minimum, because of the environmental impact from larger batteries versus smaller batteries in PHEVs or BEVs of various sizes, future policies should somehow consider this. See section 1.6 above and policy recommendations in section 2.8 below.

2.7 Reform other regulations (e.g., EU, UK, Canada, US) to allow LR-PHEVs as a long-term solution (no sunset) with conditions.

Currently the US and CARB do not have technology-forcing regulations for low-emission, light-duty vehicles. Canada recently replaced its mandate for EVs with a more flexible greenhouse gas standard for automakers to meet (2027 – 2032) [20]. The UK claims it has the most ambitious zero-emission vehicle mandate in the world and Vehicle Emissions Trading Scheme that requires only BEVs and FCEVs to be sold as new vehicles after 2034 with no PHEVs allowed to be sold in 2035 and later years [29]. The European Commission recently proposed to modify the European Union's current mandate [30] that 100 percent of new light-duty vehicle sales in 2035 be BEVs and fuel cell EVs to allow a few PHEVs to be sold in 2035 and later years [31]. Specifically, from 2035 onwards, automakers will need to comply with a zero grams per km tailpipe GHG emissions reduction requirement for 90% of light-duty vehicles sold, while the remaining 10% emissions will need to be compensated through the use of low-carbon steel made in the Union, or from e-fuels and biofuels. This last provision will allow for PHEVs and other vehicles. For company cars the EU plans to remove the substantial subsidies for gasoline and diesel vehicles [31].

Regulators should reform the regulations in the US, Canada, the European Union and the United Kingdom to allow long-range PHEVs to be sold to individuals past 2035 (and not banned) without restrictions except new PHEVs in fleet vehicles and company cars provided to employees should be banned unless all subsidies for gasoline and diesel use have been removed (e.g., by EU member states). Regulators should also require light-duty automakers to meet the above requirements (sections 2.1, and 2.4), require control of high-power engine cold starts based on the ACC II regulation, and require flexible fuel PHEVs that can use E-85. Changes to test protocols to require better measurement of all-electric miles and default electric miles prior to engine turn-on should be considered.

Countries should consider the findings on mining, recycling, and battery manufacturing GHG emissions (section 2.6) and their countries unique UF curve for LR-PHEVs (section 2.5) and each country should use this data to select their own minimum AER for a long-range PHEV to be eligible to be sold long-term. Countries and states need to determine whether 2035 or a later date is the best time for a 100% requirement for only BEVs, fuel cell EVs and long-range PHEVs to be sold as new light-duty vehicles. Each jurisdiction has unique circumstances as a path to a 100% requirement is proving to be much more difficult than regulators thought a year or two ago. To this point, each jurisdiction should determine if they want to follow the recommendations in section 2.3 and cap PHEVs with 50 to 79.9 miles AER that are sold in 2035 and later years at 20% of total sales by an automaker and cap PHEVs with 80 to 119.9 miles AER at 50% and have no cap for PHEVs with 120 miles or greater AER.

2.8 Eventually, vehicle regulations should use data to verify that LR-PHEVs are matching expectations and, if not, take corrective action.

Advanced clean Cars II by CARB, the UK zero-emission vehicle program and the proposed EU automative package not only have mandates to sell vehicles but also a GHG standard for an automaker's fleet of vehicles sold. We recommend that regulators use both: the GHG standards should be designed to be equivalent to the vehicle sales mandates as far as GHG reduction so that one can be used to verify the other. Specifically, measuring actual emissions from the on-road use of LR-PHEVs should be used to verify if there's an GHG reduction short fall, which means updating the UF curve with new data for long-range PHEVs (section 2.4). There's likely a lag before in-use data from LR-PHEVs is available and processed. Challenges with data quality and possible manipulation, data privacy concerns, and complexity of large data sets can be addressed with adequate time and funding.

If the data shows that LR-PHEVs are not plugging in enough there are several possible remedies available. Utilities should provide a more compelling PHEV charging electricity rate to provide a clear advantage over gasoline. A better education campaign should be funded (e.g., at dealers and/or public advertising) or the minimum AER to qualify as a LR-PHEV could be raised. Also improvements such as using low-carbon steel in vehicles, different battery chemistry, disincentives for very heavy vehicles, efficiency improvements in heat-pump systems, or geofencing requirements for LR-PHEVs operating disproportionally impacted areas could be required for an automaker's future vehicles as a result of the verification findings in order to true-up (i.e., make-up the missed GHG reductions).

Eventually regulators should include in the verification process, additional GHG emissions from LR-PHEVs, BEVs and fuel cell EVs, including mining, recycling, battery and fuel cell and hydrogen storage manufacturing and possibly upstream GHG emissions from generating electricity, extracting and producing hydrogen, gasoline, E-85 and other allowed long-term biofuels. At minimum a verification and true-up process should be developed for the outlier cases, perhaps fuel cells using natural gas reformation or very large batteries in BEVs and LR-PHEVs. Sourcing decisions for batteries matter, and today battery carbon intensity can vary between 45 and 108 kg CO_2e/kWh and leading automakers plan to reach 20 kg CO_2e/kWh [17].

CARB should also consider the above verification process with true-up provisions in their upcoming Drive Forward Light-duty Vehicle regulations so that automakers can further lower emissions, if needed. A verification and true-up process also is needed if the GHG emission standard is higher than zero grams per mile (e.g., the December 2025 proposed revision to the EU zero-emission vehicle mandate).

2.9 Taxation and road use fees in countries should account for environmental difference between electricity and other fuels.

More countries, states and provinces are shifting to per-mile fees to pay for road and bridge building, repair and maintenance or considering this, to replace annual vehicle registration fees. Per-mile fees for PHEVs should charge less for electric miles than for gasoline, diesel, E-85 and most other fuels to reflect the environmental benefits of electric miles. However, doing this is complicated because of per-gallon taxes on gasoline and other non-electric fuels and because of other environmental policies such as cap-and-invest and clean fuel standards which impose costs on fuels with higher greenhouse gas emissions. At minimum, a country or state should not have both vehicle registration and per-mile fees to pay for roads, and when designing or reforming a per-mile fee, the discount provided to electric miles should be based on a comprehensive analysis including costs of clean fuel standards and cap-and-invest programs to gasoline, diesel and the various alternative fuels (e.g., E-85, renewable gasoline, renewable diesel).

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