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IEEE-USA WHITE PAPER

ELECTRIFIED TRANSPORTATION

AN ADDENDUM TO IEEE-USA'S NATIONAL ENERGY POLICY RECOMMENDATIONS

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About this IEEE-USA Report:

This IEEE-USA White Paper was prepared by the IEEE-USA Energy Policy Committee (EPC) with special assistance from EPC member Veronika Rabl (lead) and EPC 2021 Chair Thomas Pierpoint. It represents the considered judgement of a group of U.S. IEEE members with expertise in this field. This document does not constitute a formal position statement of the IEEE-USA. Its contents do not necessarily reflect the views of IEEE-USA, IEEE, or the other IEEE organizational units. IEEE-USA has issued this White Paper to enhance knowledge and promote discussion of the issues addressed.

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SUMMARY

This White Paper provides detailed background information and expands on the key actions that IEEE-USA believes are necessary to reduce U.S. national security risks by transforming transportation.

Most of the impetus for the current move to electrify transportation is driven by energy and environmental benefits. While these benefits are significant, there is another aspect that should be taken into consideration – energy security.

Transportation is almost entirely dependent on oil and consumes most of the petroleum used in the United States. Dependence of a critical economic sector on a single fuel represents a serious threat to national security.

Ninety percent of the energy used in transportation during 2019 came from oil[1], an energy source subject to potential disruptions due to events beyond the control of the U.S. During the same period the transportation sector consumed more than 70 percent of all petroleum used in the United States. Oil will continue to be a major fuel for decades, but our ability to reduce petroleum use will be essential to mitigating the national security risks inherent in dependence on a single energy source for transportation. An efficient way to curtail dependence on petroleum is to expand electrification of mass transit, passenger and commercial vehicles, buses and rail. Continuing to develop alternative fuels and implement natural gas vehicles are also necessary to satisfy the continuing requirement for liquid fuels.

Electrifying transportation increases energy efficiency and reduces pollution.

Energy use in transportation exceeds the amount of energy used to generate electricity; only fundamental changes in transportation efficiency can alter this equation. Electrification represents such a fundamental change. Electric motors are inherently more efficient than internal combustion engines and can be used in mass transit, passenger and commercial vehicles, buses and rail. For example, electric vehicles convert about 59-62 percent of the grid's electrical energy to power at the wheels compared to conventional gasoline-powered vehicles, which convert only about 17-21 percent of the energy stored in gasoline to power at the wheels.[2] Conservatively, these percentages translate to a well-to-wheels efficiency of about 20–21 percent for electrics and about 15–19 percent for conventional cars.[3] Conventional hybrid vehicles have already demonstrated the capability to increase fuel economy by adding a small battery and electric motor to level the load. The plug-in feature adds an option to substitute electricity for some, or all, of the gasoline used in the vehicles.

We need a radical transformation of the transportation sector, not only to reduce its complete dependency on oil, but also to reduce emissions, particularly in large cities. Gasoline combustion

1 *EIA Monthly Energy Review*, May 2020, www.eia.gov/totalenergy/data/monthly/index.php#petroleum

2 USDOE, *Energy Efficiency and Renewable Energy*, www.fueleconomy.gov

3 Using 34% well-to-plug efficiency for electricity (see, e.g., *LLNL Energy Flow*, April 2018); and 10% loss for petroleum refining and transport.

is responsible for most precursors of urban smog. In addition, fuel combustion from transportation contributes about 30 percent[4] of U.S. greenhouse gas emissions, exceeding those due to power generation. Because transportation emissions are widely dispersed, it is impractical and uneconomical to capture and store transportation emissions once they are emitted. A taste of what clean air feels like was offered by the 2020 pandemic. NASA satellite measurements revealed a 30% reductions in air pollution over the major metropolitan areas of the Northeast United States.[5] Similar reductions have been observed in other regions of the world. A brief summary of the changes in the transportation sector caused by the pandemic can be found in Dr. Novosel's interview with Energy Daily.[6] Even with the current generation mix, electrifying the transportation sector has the potential to increase transportation energy efficiency and reduce both greenhouse gas and criteria pollutants. Such factors take into account on-road performance, battery manufacture and battery disposal, recycle and reuse.[7] Continuing advances in batteries and ultra-fast charging are some of the options[8,9] that are being pursued to reduce "range anxiety."

Appropriate market signals accelerate progress

The U.S. electric infrastructure already in place is sufficient to permit a significant reduction in dependence on liquid fuels through greater penetration of plug-in electric vehicles (PEVs), including all-electric and plug-in hybrid electric vehicles. Vehicle electrification would produce a direct and immediate domestically-produced substitute for oil, along with commensurate benefits for energy efficiency, national security, and the environment.

Automobile, bus, ship, train and truck manufacturers are now rapidly developing and commercializing more efficient electric drivetrain technologies. In the United States, Tesla, Chevrolet, Nissan, Toyota, and other manufacturers have released all-electric or plug-in hybrid designs for the mass market. Outside the United States, manufacturers such as Volvo, Mercedes, BMW, Hyundai and others have also entered this market. China has established a goal to have five million electric vehicles on the road by 2020 – expected to be delayed by the COVID-19 events. In an effort to clean up some of world's most polluted cities India has announced a target to sell only electric vehicles by 2030. The world is moving toward electric vehicles as these vehicles become more cost effective to buy.

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4 *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018*, EPA April 2020

5 NASA Satellite Data Show 30 Percent Drop In Air Pollution Over Northeast U.S., NASA, April 2020; https://www.nasa.gov/feature/goddard/2020/drop-in-air-pollution-over-northeast

6 "Electrify vehicle fleets and transportation sector will follow," *Energy Daily*, May 27, 2020

7 See, e.g., *Environmental Assessment of a Full Electric Transportation Portfolio*, EPRI-NRDC, September 2015; https://www.epri.com/research/products/000000003002006881

8 *Advanced Battery and Electrification Research to Enable Extreme Fast Charging*, U.S. DOE, April 30, 2018; https://www.energy.gov/articles/department-energy-announces-19-million-advanced-battery-and-electrification-research-enable

9 *Enabling Fast-Charging: A Technology Gap Assessment*, U.S. Department of Energy, Office of Efficiency & Renewable Energy, October 2017; https://www.energy.gov/sites/prod/files/2017/10/f38/XFC%20Technology%20Gap%20Assessment%20Report_FINAL_10202017.pdf

INTRODUCTION

The transportation sector is vital to our economy, but it is highly influenced by uncertainties in oil supply and cost. Today, about 40 percent of U.S. energy is used by transportation. Transportation is also the single largest U.S. petroleum user; it consumes about 70 percent of all petroleum used in the United States.[10] Although oil will continue to be a major transportation fuel, our ability to develop effective substitutes for its transportation use will be essential to reducing the national security risks inherent in dependence on a single energy source. A single substitute would be an effective first step, but it is not sufficient. Flexibility — the ability of vehicles and fueling systems to adapt quickly to rapid changes in technologies, price regulation and market conditions--will be key to reducing national security risks.

Consequently, a radical transformation of the transportation sector should aim not only to reduce its complete dependency on oil, but also to increase system efficiencies and reduce emissions in the transportation sector, particularly in large cities. Because transportation emissions are widely dispersed, it is unlikely that these emissions could ever be captured and stored. Hence, the principal option is to substitute alternate, cleaner, energy sources for oil.

A portfolio approach would enable the transformation away from oil, particularly substitutes with electricity or alternative liquid fuels. Ideally, this perspective would entail rapid deployment of vehicles, giving the consumer the power to shift, from one day to the next--between petroleum, electricity, ethanol; and new types of alternate liquid fuel, less expensive and friendlier to the environment than the high purity, corn-based ethanol in common use today. Indeed, it should be noted that not all biomass fuels reduce carbon emissions; some applications may result in large increases of air emissions.[11,12,13]

IEEE members are passionate about Electric Transportation and have formed the IEEE Transportation Electrification Community (TEC).[14] The TEC discusses the technologies, organizations and projects that will enable the clean, connected and efficient transportation and vehicular systems of the future, including electric and hybrid cars and trucks, more electric aircraft, electric rail and light rail systems, electric ships, off-road vehicle systems, and other forms of personal and mass more-electric transportation. The community also discusses key enabling technologies, including batteries, battery charging and management, power electronics, electric motors and drives, networked vehicles, fuel cells, high-power wireless power transfer, and other forms of energy storage. The community takes a leadership role in vehicle to grid (V2G) and grid interaction issues, IEEE

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10 U. S. Energy Information Administration, *Monthly Energy Review*, May 2020, Tables 3.7a–3.7c; http://www.eia.gov/totalenergy/data/monthly/#petroleum.

11 See, for example, May 8, 2015, letter to EPA from Massachusetts Senators Markey and Warren (http://www.biologicaldiversity.org/programs/climate_law_institute/pdfs/EPABioenergyCleanPowerPlan_05-08-15.pdf)

12 T. Buchholtz and J. Gunn, "Carbon Emission Estimates for Drax Biomass Power Plants in the UK, sourcing from Enviva Pellet Mills in U.S. Southeastern Hardwoods, using the BEAC model," Spatial Informatics Group, May 2015; https://www.southernenvironment.org/uploads/audio/2015-05-27_BEAC_calculations_SE_hardwoods.pdf

13 "Think Wood Pellets Are Green? Think Again." NRDC issue brief IB:15-05-a, May 2015

14 https://tec.ieee.org/

Standards in transportation and vehicles, high-performance electric traction, student electric vehicle competitions, and vehicle intelligence.

The TEC provides leadership on the development of needed IEEE standards. The TEC also provides conferences, workshops, publications, newsletters and webinars related to Transportation Electrification.

The following sections that follow provide more detailed information and expand on the key actions IEEE-USA thinks are necessary to reduce U.S. national security risks by transforming transportation.

ELECTRIFYING TRANSPORTATION: ELECTRIC VEHICLES

One of the most effective avenues for reducing near-term (primary) energy use in the transportation sector is electrification. The electricity infrastructure is in place and the market for electric vehicles continues to grow.[15] In addition to substituting for oil, electrification increases overall transportation system efficiency.[16] In fact, an electric vehicle uses about a half of the primary energy of a conventional vehicle.[17] If the electricity to run the vehicles is produced by nuclear, hydro, wind, or solar no carbon dioxide is released during production and none while the electricity in the battery runs the vehicle. In fact, ***electric transportation improves overall energy efficiency and reduces greenhouse gas emissions even when electricity is produced from the currently installed generation capacity mix.***[18] Increased use of natural gas for generation is making the environmental advantage even more prominent. The finding of major reductions in greenhouse gas emissions continues to be challenged from-time-to-time. A recent comparison of numerous studies confirms the findings both in the U.S. and in Europe.[19] ***Electrification opens up a clear pathway to near-zero "well-to-wheels" emissions in the transportation sector.***

Hybrid electric vehicles (HEV) were introduced into the U.S. transportation market in 1999, representing the first step towards electrification. While initially a rarity, they are now a fairly common sight on the roads. These vehicles generate electricity on-board and use a small battery to supplement the gasoline engine, as needed, to increase its efficiency. Fossil fuel is the only energy source for this automobile.

15 See, for example, U.S. DOE, U.S. Plug-in Electric Vehicle Sales, Alternative Fuels Data Center, https://afdc.energy.gov/data/10567

16 See, for example, *Environmental Assessment of Plug-In Hybrid Vehicles, Vol. 1: Nationwide Greenhouse Gas Emissions*, EPRI-NRDC July 2007

17 See, for example, *Electrification Scenarios for New York's Energy Future*, EPRI, February 2020.

18 See, for example, *Advanced Energy Technologies for Greenhouse Gas Reduction*, AEE 2014; https://www.aee.net/initiatives/epa-111d.html#epa-technlogies-for-greenhouse-gas-reduction

19 *Factcheck: How electric vehicles help to tackle climate change*, CarbonBrief, February 2020; https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change

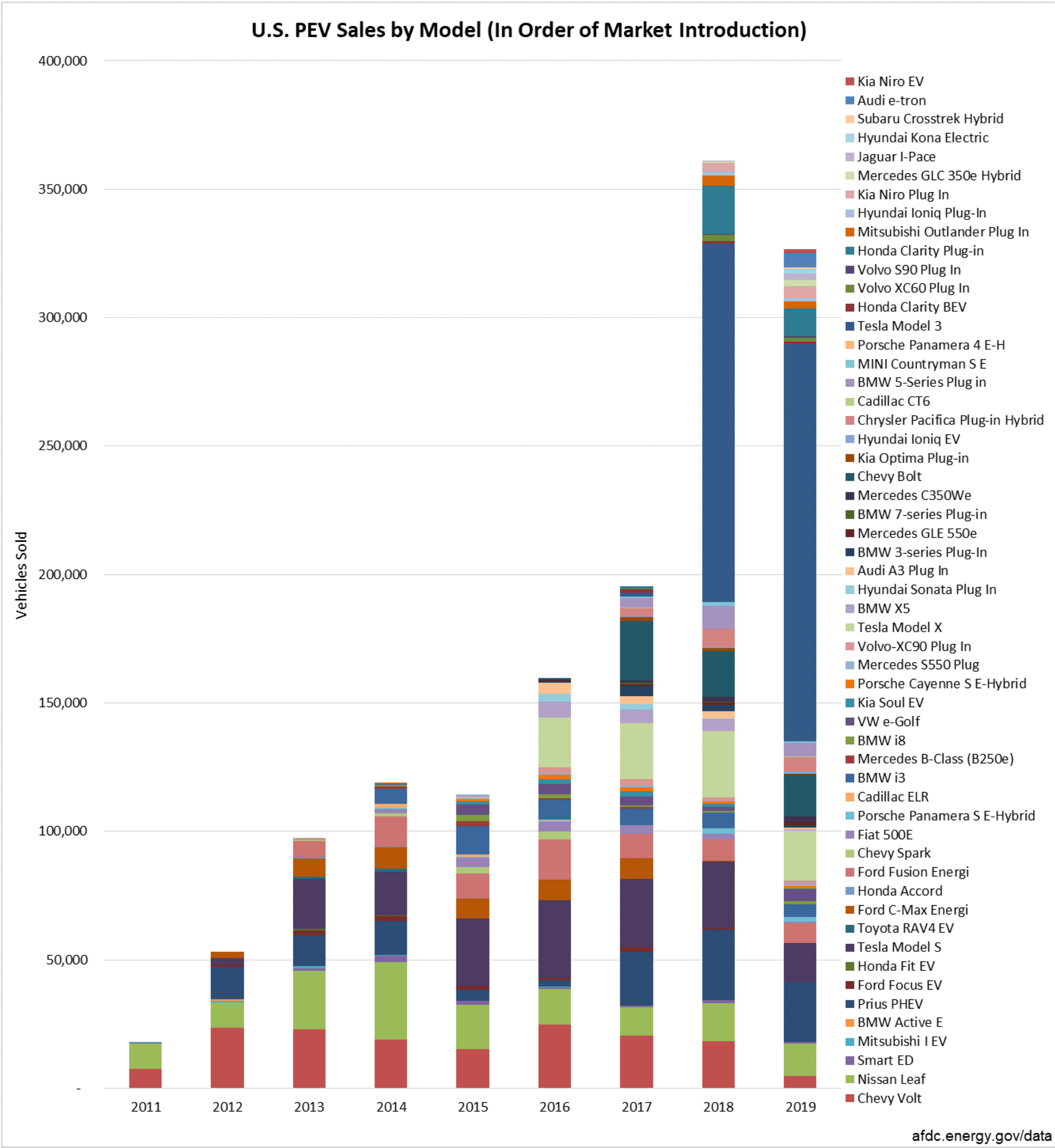
To substitute electricity for some, or all, of the fossil fuels requires a new class of vehicles that users can charge through an electric plug. These vehicles fall into two basic categories:

- Plug-In Hybrid Electric Vehicles (PHEV) – similar to conventional Hybrid Electric Vehicles (HEV), except for a larger battery and the ability to charge the battery directly from an electric socket
- Battery Electric-Only Vehicles (BEV) – all electric-drive vehicles with no supplemental engine

The most important electrification target should be light-duty (LDV) and heavy-duty vehicles (HDV — primarily freight trucks, but also buses). These two uses represent about 60 percent and 25 percent of transportation energy use, respectively.[20] Target markets could include both individual-owned vehicles as well as fleets (for example, delivery services, rental cars and buses).

Through 2019, more than five million HEVs (since 1999 market introduction)[21] have been sold in the United States and almost 1.5 million plug-in electric vehicles (PEVs) (since 2010 market introduction), including over 300 thousand PEVs[22] sold in 2019 alone. As can be seen in the Figure below, almost half of these were Tesla Model 3. ***The 2019 total is about the same as the total number of plug-in vehicles sold during the first five years after their market introduction.*** Most major automakers have PHEVs or BEVs on the market. Plug-in hybrids and all-electrics combined accounted for 2.1% of the light vehicle market in 2019, compared to conventional hybrids which captured 2% of the market in 2019.[23] As outlined below, further electrification can result in further increase of transportation energy efficiency, reduced maintenance costs, and reduced air emissions.

20 U.S. DOE, Alternative Fuels Data Center, Transportation Fuel Use by Mode, May 2019; https://afdc.energy.gov/data/10566
21 Light Duty Electric Drive Vehicles Monthly Sales Updates, Argonne National Laboratory, https://www.anl.gov/es/light-duty-electric-drive-vehicles-monthly-sales-updates
22 ibid
23 Transportation Energy Data Book, Oak Ridge National Laboratory, April 2020; https://tedb.ornl.gov/wp-content/uploads/2020/02/TEDB_Ed_38_04302020.pdf



Source: U.S. DOE Alternative Fuels Data Center; https://afdc.energy.gov/data/10567

PEVs operate some, or all, of the time in an electric mode using grid-supplied electricity generated from diverse domestic energy sources such as renewables, gas, coal, and nuclear. A PHEV uses a modest-sized battery designed for an all-electric range of ten to 40 miles.[24] Because U.S. owners, on average, drive light-duty vehicles (LDVs) less than 40 miles a day, and the average trip is only about 10 miles, PEVs could serve about half of LDV miles by using electricity. Electric-only vehicles completely eliminate the consumption of liquid fuels. In case of a sudden price shock or international crisis, most PEV users could continue to go to work, as well as do essential shopping

24 See EPA (http://www.fueleconomy.gov/) for data on individual vehicle models.

every day. Being able to sustain such activities would substantially enhance the ability of the U.S. and OECD economies to cope with such events.

PEVs make possible the conversion of many vehicle functions that are currently either mechanical or hydraulic to electricity because of on-board electric power that well exceeds what is available from a traditional alternator. Such conversions create new avenues for reengineering the car, including new efficiency improvements and reduction in moving parts, with an attendant reduction of owner maintenance costs. For example, electromagnetic valve lifters designed to keep the engine operating at its optimal point are practical in PEVs. Using electric motors and power electronics for the vehicle drive train can eliminate gearboxes and greatly simplify transmission design and vehicle maintenance. PEV drive trains also permit capture of energy that would normally be expended heating brake liners during vehicle slowing. In addition, the electric drive allows the vehicle's combustion engine to operate in a more efficient power cycle. In general, the technologies in PEVs are much newer than those in internal combustion engines, which suggests that there is far more room for improvements in this technology given continued R&D and market incentives.

Rail electrification offers further opportunities for zero-emission, zero-oil freight and passenger transportation. If high-traffic rail lines were electrified and powered in part by renewable energy sources, carbon emissions and oil consumption would be reduced nationwide. An obvious target for electrification is increased reliance on light rail, a form of urban rail public transportation that generally has lower capacity and lower speed than heavy rail and metro systems, but higher capacity and higher speed than traditional street-running tram systems. Light rail typically refers to rail systems with rapid transit-style features that use electric rail cars, operating mostly in rights-of-way separated from other traffic.[25]

Amtrak operates the busiest intercity electrified corridor in the nation from Boston to Washington, D.C., through New York City. Many other electrified rail lines serve both regional commuters and freight. The relationship with passenger rail operators enables partnerships that could take additional commuters out of their cars and onto trains.

The transportation electrification strategy has challenges to overcome before reaching a broad-based electrified transportation system. A focus on the following areas will help to meet these challenges:

- Deployment of PEVs and HEVs
- Improved battery technology
- Development and deployment of battery charging infrastructure
- Integrating PEVs into the electric grid operations
- Reduced weight, volume and cost of power electronics and electric machines for PEVs

25 See e.g., Light Rail, in Wikipedia, http://en.wikipedia.org/wiki/Light_rail

We address each of these focus areas in detail below.[26]

PEV Deployment and Electrical Load Impacts

Light-duty vehicles (LDV) are used mainly for passenger transportation and come in a variety of body styles--such as cars, vans, SUVs and pickup trucks. As of 2017 the United States had registered about 250 million such vehicles.[27] During the period of 2015 to 2019 new LDV sales have been close to 17 million/per.[28] At this rate, it would take about 10 years to electrify one-half of American vehicles even if the entire new car market were to be converted to PEVs.

Some are still concerned that widespread PEVs deployment will potentially overload the grid. We now understand such concerns much better. Early studies by PNNL29 and ORNL30 suggested that existing generation resources could power more than half of all LDVs. More recent studies conclude that ***"sufficient energy generation and generation capacity is expected to be available to support a growing EV fleet as it evolves over time, even with high EV market growth."*** 31 In a worst case, unmanaged charging scenario 6 million new EVs correspond to about 12 GW of aggregate demand. To put this figure in perspective, over the past decade the U.S. electric power system added an average dispatchable32 generating capacity of 12 GW per year, even though there was virtually no growth in electric energy requirements. Impact on electric energy use is estimated in a recent EPRI report.33 In its Reference scenario EPRI projects that by 2030 electricity will power approximately a quarter of vehicle miles traveled, rising to 70% by 2050. This level of electrification means that EVs and PHEVs reach around 40% of new vehicle sales by 2030, and around 75% by 2050. According to the study this results in a cumulative electrical load growth of about 30% by 2050, which implies a modest 0.8% annual growth rate. Without efficient electrification, EPRI projects that electricity use will decline, driven by efficiency gains. However, this electrification scenario yields a

26 A substantial amount of material included in this section has been extracted from the *IEEE Report to DOE QER on Priority Issues*, prepared by the IEEE Joint Task Force on Quadrennial Energy Review, September 5, 2014 (http://www.ieee-pes.org/images/pdf/IEEE%20QER%20Report%20September%205%202014%20HQ.pdf and http://www.ieee-pes.org/images/pdf/IEEE%20QER%20Summary%20Report%20September%205%202014%20HQ.pdf)

27 Bureau of Transportation Statistics, National Transportation Statistics, Table 1-11: Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances (Updated May 2019), https://www.bts.gov/content/number-us-aircraft-vehicles-vessels-and-other-conveyances

28 See, for example, Federal Reserve Bank, Economic Research, https://fred.stlouisfed.org/series/ALTSALES

29 Kinter-Meyer, M., K. Schneider, and R. Pratt, Impact Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids. Part 1: Technical Analysis; Pacific Northwest National Laboratory, Richland, WA, 2007; http://energyenvironment.pnnl.gov/ei/pdf/Impact%20Assessment%20of%20PHEV%20on%20US%20Power%20Grid.pdf

30 Hadley, S. W., and A. Tsvetkova, Potential Impacts of Plug-In Hybrid Electric Vehicles on Regional Power Generation; ORNL/TM-2006/554; Oak Ridge National Laboratory, Oak Ridge, TN, 2008; http://web.ornl.gov/info/ornlreview/v41_1_08/regional_phev_analysis.pdf

31 *Summary Report on EVs at Scale and the U.S. Electric Power System*, U.S. DRIVE Partnership, November 2019.

32 Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators or of the plant owner; that is, generating plants that can be turned on or off, or can adjust their power output according to an order. Most dispatchable generation is fossil fueled or hydro.

33 *U.S. National Electrification Assessment*, EPRI, April 2018

60% drop by 2050 in final energy use for light-duty vehicles despite an assumed increase in vehicle miles traveled of almost 30%.

It is obvious from these and other studies[34] that explore the impact of widespread electrification, managed (smart) charging is a critical element affecting the ultimate grid impact of EVs. Most charging will have to occur off-peak. This can be accomplished through one or more measures, such as tariffs, built-in charging algorithms, demand limiters, and smart controls. It should be noted that TOU (time-of-use) rates alone may not reduce the peak demand because while do shift load to off-peak hours, they do not induce load leveling. In fact, they may increase demand by clustering the start of many appliances to the start of the off-peak period. One of the Smart Grid studies assumed that ***PEV charging would be managed as an integral element of grid operating processes and estimated the current grid can accept eight to 12 million PEVs, with little impact on generation and transmission***.[35]

As discussed above, no major impacts on generation capacity are expected at this time. The specifics will vary from region-to-region, depending on the load profiles prior to large-scale introduction of PEVs. It may also be necessary to review potential transmission congestion issues to assure adequate capacity to meet the charging needs. Of more concern is some of the existing distribution infrastructure, which may not be able to accept PEVs without some rework. The peak demand imposed by the PHEV and BEV on the grid depends on the size of the on-board battery, the owners' driving patterns, the charging strategy, and the charger characteristics. A number of studies have developed, and continue developing, the actual electricity use data needed to establish the impact on the power system. Some of the readily available data include The EV Project[36] and indicate an average of 5 to 10 kWh/day. San Diego Gas Electric suggests a range of 6 to 8 kWh/day for PEV.[37] The more powerful chargers will result in much higher demand than that imposed by charging through a conventional plug. Several electric vehicles on one residential street could overload the local distribution transformer[38] unless power companies implement demand management measures to enforce load diversity and prevent a possible overload. Ample experience already exists with the success of such controls, which have been widely applied to off-peak heating and water heating.[39]

34 *Electrification Futures Study*, National Renewable Energy Laboratory, June 2018

35 Fang, X., S. Misra, G. Xue, and D. Yang, "Smart Grid - The New and Improved Power Grid: A Survey," Communications Surveys and Tutorials, IEEE (Volume: 14, Issue: 4) October 2012. Available: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6099519&sortType%3Dasc_p_Sequence%26filter%3DAND%28p_IS_Number%3A6341161%29

36 Education and EV Project Expansion FAQs, The EV Project, U.S. DOE and ECOtality; http://www.theevproject.com/education.php

37 "The ABCs of plug-in EVs," SDG&E, 2011. Available: https://www.sdge.com/sites/default/files/documents/The%20ABCs%20of%20Plug-In%20EVs.pdf

38 Interview with S. Rahman, "Going Electric: Things to Consider" (*The Institute*, September 2011), http://theinstitute.ieee.org/ieee-roundup/opinions/ieee-roundup/electric-vehiclespossibilities-challenges-and-their-impact)

39 See, for example, IEEE Tutorial Course: *Fundamentals of Load Management*/89Eh0289-9-Pwr (1988)

Given the concerns, EPRI has analyzed distribution system impacts of PEV charging[40] and concluded that:

- Diversity of vehicle location, charging time, and energy demand will minimize the impact to utility distribution systems
- Level 1 (standard residential voltage; no extra cost) charging generates the fewest distribution system impacts
- Higher power, Level 2 (208 or 240 V) charging, generates larger system impacts, and is typically not required for most customer charging scenarios with light-duty vehicles
- Short-term PEV impacts for most utility distribution systems are likely minimal and localized to smaller transformers and other devices where the available capacity per customer is already low
- Controlled or managed charging could defer system impacts for a significant period of time

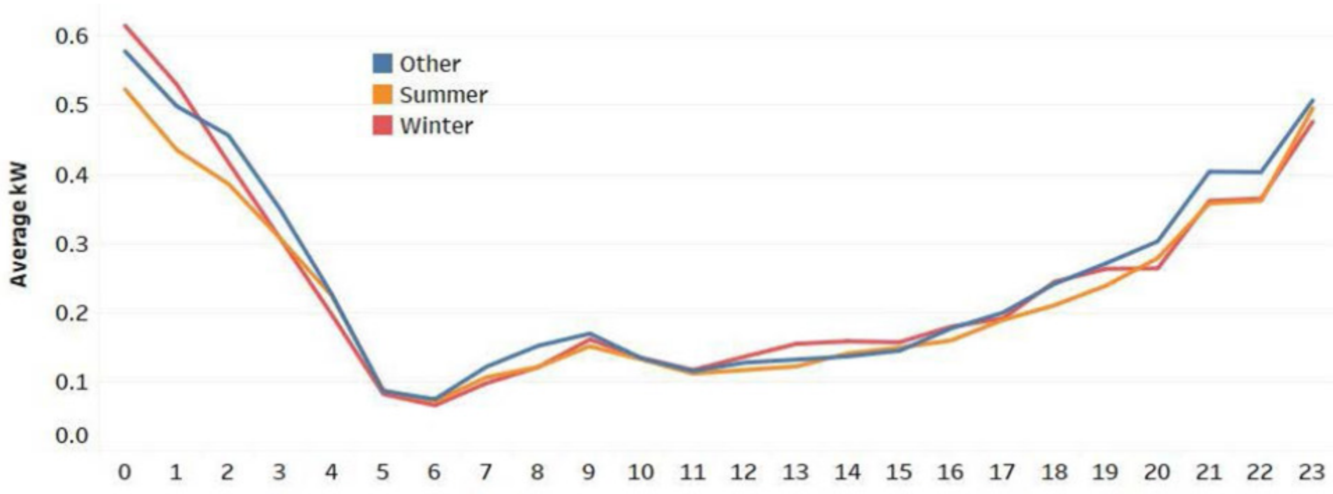
EPRI further concluded that utilities could fully mitigate potential electric grid stresses through asset management, system design practices, and, at some point, managed PEVs charging to shift the load away from system peak. A proactive approach of understanding where PEVs are appearing in their system, addressing near-term localized impacts, and developing both customer programs and technologies for managing charging loads is most likely to effectively and efficiently enable even very large-scale PEV adoption.

The demand and energy impacts are now being confirmed in a series of field test conducted by utilities and EPRI. The first such effort was recently completed with the Salt River Project (SRP), where about 100 vehicles were monitored over an 18-month time period.[41] The findings were consistent with prior data and estimates. The key findings included the following:

- EVs use approximately 2,700–3,300 kWh per year; this is consistent with the generally accepted PEV “efficiency” of 3-4 miles/kWh.
- While DC Fast charging comprised less than 3% of the total energy used in the study, DC Fast charging drove short-duration peaks observed about 1% of the time.

40 Maitra, A., *Preparing the Distribution Grid to Embrace PEV*, September 2012 (http://www.naefrontiers.org/File.aspx?id=35967)
41 *Electric Vehicle Driving, Charging, and Load Shape Analysis : A Deep Dive Into Where, When, and How Much Salt River Project (SRP) Electric Vehicle Customers Charge*, EPRI, July 2018

Of particular interest are the load shapes, such as the ones shown in the Figure below.



Source: ***Electric Vehicle Driving, Charging, and Load Shape Analysis : A Deep Dive Into Where, When, and How Much Salt River Project (SRP) Electric Vehicle Customers Charge*, EPRI, July 2018**

Electrifying transportation would have additional benefits beyond national security and energy independence--it represents a major potential area of economic development and growth. The need for charging stations alone requires creating an entire new industry for producing, maintaining, and managing the charging infrastructure.

Electric Vehicle Charging Equipment (EVSE)[42,43]

The simplest form of battery-charging infrastructure are standard electric plugs (Level 1 charging). Ready access to such plugs would meet the needs of almost half of U.S. drivers. Higher charging rates can be provided through Level 2 charging stations, which may use residential 240 V plugs, or high-power commercial/industrial DC stations designed for rapid (fast) charging.[44]

Studies are usually focused on residential charging because 80-85% of all charging for cars is expected to occur at home with at most Level 2[45] charging (3-7kW). Fast charging is then located along highway corridors and in some public areas.

While light duty vehicles are expected to be charged at residences, where chargers will max out at 10kW for Level 2 charging. However, the challenges are greater for commercial and fleet vehicles due to vehicle battery sizes and logistics. Fast charging becomes a requirement for those vehicles.

42 EVSE stands for Electric Vehicle Supply Equipment

43 Portions of this section have been adapted from *Energy Storage Opportunities and R&D Needs*, IEEE PES, 2020

44 See, for example, IEEE Transportation Electrification website (http://electricvehicle.ieee.org/search-results/?q=charging%20options) or DOE Alternative Fuels Data Center (http://www.afdc.energy.gov/fuels/electricity_infrastructure.html)

45 The various PEV charging alternatives are discussed in *Developing Infrastructure to Charge Plug-In Electric Vehicles*, U.S. DOE Alternative Fuels Data Center; https://afdc.energy.gov/fuels/electricity_infrastructure.html

Though it is understood that, in total number of vehicles, fleet applications make up a smaller fraction than personal use vehicles, the charging sizes to support the segment will be larger. DC fast chargers were first deployed at 50kW, but are now being introduced at sizes of 150kW, 250kW, with announcements of extreme fast 350kW chargers – 30 times the size of standard Level 2 home chargers.

The increasing size of chargers changes the dynamics of evaluating the impact of charging stations on a grid. Chargers will impact the grid across five (5) segments:

- Light Duty Vehicles – mostly Level 2 charging – approximately 85% charging at residences and a one to one relationship – where planning impact is estimating by the year on year vehicle adoption multiplied by the size of the charger (Level 2 – 7.5kW)
- Workplace Charging – where business and office parking structure will provide Level 2 chargers for daily charging of parked vehicles and 2-4 fast chargers for workers looking for a quick charge before leaving work
- Public Charging Plugs (slow) – typically free charging sites
- Corridor Charging – along highways, aimed at fast, short duration charging. The typical size charger will be a minimum of 150kW (30-minute charging target), located along highway travel plazas, and will contain 2-4 chargers
- Fleet Charging – Charging that will occur at fleet depots, from medium size to light duty trucks. Minimum 10 chargers per site, likely 50kW + chargers. Sites will occur at distribution centers.

One of the steps that would greatly aid PEV penetration would be advances in standardization of the plug form factor.[46] This is not just a U.S. issue, Europe and Japan each have settled on different plugs an issue that is likely become more controversial as the PEV world moves to ubiquitous fast and extreme fast chargers. To quote Andrew Tanenbaum[47] "The nice thing about standards is that you have so many to choose from; furthermore, if you do not like any of them, you can just wait for next year's model."

46 See, for example, "Competing Electric Car Charging Standards Can Be Easily Fixed," *Forbes*, December 19, 2019

47 Andrew Tanenbaum, *Computer Networks*, 2nd ed., p. 254

Deploying Battery-charging Infrastructure

As of June 2020 almost 30,000 public charging stations were in place in the U.S..[48] Although the number of chargers has grown rapidly the gap between projected EV adoption and planned charging stations is still large. A study by the International Council on Clean Transportation estimates that only one-fourth of the charging infrastructure that will be needed by 2025 has been built as of 2017.[49] Reflecting the worldwide interest in EVs, Plugshare shows more than 300,000 charging locations worldwide,[50] including many private chargers owners are willing to share with other travelers.

To help accelerate the PEVs adoption, eight states have formed an electric vehicle compact.[51] These states include California and New York, accounting for almost 30% of the total U.S. vehicle market. The compact's goal is to develop infrastructure, coordinated policies, codes and standards, and a consumer market to put more than 3.3 million ZEVs (zero-emission vehicles) on the roads in those eight states by 2025. Work is underway to build a West Coast Green Highway, an electric EV charging network connecting British Columbia to Baja, California (BC to BC) with DC fast charging stations located every 25 to 50 miles along Interstates and major highways.[52] A similar initiative is now in place for the Northeast corridor, from the Washington, DC, area to Maine.[53] Other regional programs are likely to follow.

Improving Battery Technology

The battery is a key component of electric vehicles and its cost is the principal barrier to rapid PEV penetration. One of the concerns about battery costs relates to availability of some of the critical materials, particularly lithium and cobalt. Most of the world's lithium reserves are in Bolivia, Chile and China, therefore its supply may be subject to political considerations. However, the lithium industry is expanding. New players, like Australia, have been moving quickly using new technology. There is now a general agreement that Li-ion battery chemistry has great potential for substantial cost reduction and lithium shortage are not expected in the foreseeable future.[54]

Some have voiced concerns about batteries' environmental impacts; including concerns that, in some cases, battery production is large enough to negate the environmental benefits of electric transportation. In fact, ***Li-ion battery production and disposal for electric vehicles represents***

48 *Alternative Fueling Station Counts by State*, U.S. DOE, Alternative Fuels Data Center; https://afdc.energy.gov/stations/states

49 *DC fast charging stations located every 25 to 50 miles along Interstate*, International Council on Clean Transportation, January 2019, and *Electric Vehicles: Key Trends, Issues, and Considerations for State Regulators*, NARUC, October 2019

50 PlugShare – EV Charging Station Map. https://www.mywaythere.org/evcharging.asp, http://www.plugshare.com/

51 *Multi-State ZEV Action Plan*, ZEV Program Implementation Task Force, May 2014; and Multi-State ZEV Action Plan 2018-2021, June 2018; http://www.nescaum.org/topics/zero-emission-vehicles

52 West Coast Green Highway, http://www.westcoastgreenhighway.com/

53 *Northeast Corridor Regional Strategy for Electric Vehicle Charging Infrastructure*, http://www.nescaum.org/documents/northeast-regional-charging-strategy-2018.pdf/view, https://insideevs.com/news/337845/east-coast-states-team-up-to-build-charging-network

54 Lithium supply is set to triple by 2025. Will it be enough?, S&P Global, October 2019

a small contribution to life-cycle energy use and CO2 emissions.[55] Of the materials used over the years in car batteries, nickel and cobalt are the most toxic, and therefore require the most care during handling and disposal. Over time, more benign and less expensive materials are replacing these toxic materials, which should reduce their environmental impacts. Similar changes in battery design and recycling options will continue as the industry searches for better performing and less expensive batteries.[56,57]

Other materials concerns involve the need for rare earths in producing permanent magnet electric motors. However, alternatives are available in new motor technology (like switched reluctance motors and induction motors) that have higher average efficiency, and do not require rare earths. In past decades, control issues limited the use of these cheaper and better engine designs, but several novel control technologies can overcome those problems. Companies such as Tesla and Toyota have demonstrated the required expertise and new engine technology.

Advances in battery performance and technology are being pursued to reduce cost, increase power density, extend life, reduce the probability of hazardous failure, and assure consumer safety.

- In the near term, improvements in lithium-ion battery systems engineering and management are likely to deliver some of these needs. Fundamental research is expected to improve our understanding of the electronics and chemistry interface, as it determines battery lifetime and stability.
- For the long-term, novel battery chemistries, including metal-polymer, metal-air and silicon-air, could yield more dramatic performance advances --as well as allowing the construction of batteries from more common materials.
- Advances in power electronics for PEVs are expected to reduce size and cost, improve fast-charging capability, and facilitate use of efficient motors (such as induction and switched reluctance technologies) that eliminate use of rare-earth materials.

Specific needs include extending vehicle all-electric range; increasing energy storage density; decreasing cost; improving battery life and safety; and optimizing the associated power electronics and controls. As with Li-ion, the R&D effort must remain cognizant of potential environmental issues that may arise in the course of battery production and disposal.

55 Dunn, JB; Gaines, L; Kelly, J.C.; James, C.; Gallagher, K. G.," The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction.", Energy and Environmental Science 8: 158-168 (2015)

56 "Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles," EPA 744-R-12-001, April 2013

57 Gaines, L., "The future of automotive lithium-ion battery recycling: Charting a sustainable course," Sustainable Materials and Technologies, Volumes 1–2, December 2014, Pages 2–7

Battery R&D will need to focus on the following areas:

- Increasing energy storage density
- Decreasing cost
- Increasing life
- Assuring safety
- Enabling rapid battery recharge or change-out strategies
- Identifying secondary markets for used batteries
- Recycling strategies

Additionally, while batteries are no longer suitable for vehicle use when their capacities fall below about 70 percent of design capacity, even at that level the batteries may be suitable for use in stationary storage applications and may eventually contribute to solving our large-scale energy storage needs. Recycling EV batteries is likely to be easier than lead-acid, although this is still a concern.

Integrating PEVs with the Electric Grid

With the appropriate technical and regulatory framework, PEV batteries may also be able to provide services the grid needs to balance wind variability and other variable and uncertain power resources.

A consortium of automakers and electricity utilities has been formed to address the PEV interface with the grid.[58] As stated by GM:

> "The first goal of this national effort to streamline EV charging is to develop a standardized Demand Response solution. Demand Response is the signal the utility sends to the energy management company, which tells it just how much electricity is needed. While having a single EV plugged in to charge isn't going to change the dynamics of electrical flow, once you have whole neighborhoods plugging in their cars every night after work, managing electricity becomes that much more important." [59]

The primary goal of the consortium is to develop and commercialize an Open Vehicle-Grid Integration Platform – a method for managing the PEV charging loads and delivering V2G (vehicle-to-grid) services.[60] Among others, the success of this effort depends on implementing the protocol in PEVs so as to facilitate full reciprocity in assuring the vehicle is charged when needed and providing

58 *EPRI, Utilities, Auto Manufacturers to Create an Open Grid Integration Platform for Plug-in Electric Vehicles*, July 2014; http://www.epri.com/Press-Releases/Pages/EPRI,-Utilities,-Auto-Manufacturers-to-Create-an-Open-Grid-Integration-Platform.aspx

59 "GM Joins National Smart Grid Consortium," *Clean Technica*, August 2014; http://cleantechnica.com/2014/08/06/gm-joins-national-smart-grid-consortium/

60 *Open Vehicle-Grid Integration Platform: General Overview*, EPRI, July 2016; https://www.epri.com/research/products/000000003002008705

the equivalent of a vast battery storage capacity for use in managing the operations of the power system.

It is expected that operational aspects of grid integration of PEVs will be handled primarily by the appropriate elements of the Smart Grid. A NIST-led effort[61] is developing architecture that identifies the actors and interfaces related to PEV communications, control, metering, accounting, and settlement. The Smart Grid effort resulted in:[62]

- Defining a conceptual architecture for integrating communications, control, and PEVs into the grid. For example, the architecture includes separate PEV sub-metering to support pricing arrangements and vehicle-to-grid accounting.
- Accelerating standards development to support PEV-related requirements
- Identifying cybersecurity issues related to PEV communications, and incorporating PEV standards into the Smart Grid Catalog of Standards--after cybersecurity review
- Identifying the significant privacy issues associated with PEV communications, control and especially, metering and accounting
- Developing a four-stage roadmap for electric vehicle deployment and identifying the challenges and issues to be addressed to reach each stage -- including eliminating functionality barriers and advancements

The levels of grid interaction described above require increasing levels of communication and control. A number of elements are involved in these functions, including:

- The vehicle
- The charging station
- The premises network (home, building, commercial, or industrial site)
- The Load Serving Entity and/or aggregator that coordinates numerous loads for the grid
- Transmission and distribution grid operator
- Entities that manage accounting, billing and settlement

Proper coordination among these elements will be needed to fully realize the benefits of vehicle-to-grid energy exchange functions. Among others, the system will have to be designed to properly control the charging, limiting demand peaks and shifting electricity use to times with adequate generation capacity. Ultimately, ***PEV charging has to be treated as one of the flexible grid resources.*** The feasibility and benefits of this approach has been shown in a number of tests conducted by PEV manufacturers and utilities or grid operators.[63]

61 http://www.nist.gov/smartgrid

62 https://smartgrid.ieee.org and http://www.nist.gov/smartgrid

63 See for example *EV Managed Charging: Lessons from Utility Pilot Programs*, Smart Electric Power Alliance (SEPA), July 2019; https://sepapower.org/knowledge/ev-managed-charging-lessons-from-utility-pilot-programs/ and *BMW I ChargeForeward:*

While it is important to integrate PEVs with the Smart Grid, such integration raises numerous cybersecurity and privacy issues. Examples include:

- Location and movement tracking — concern that a PEV could be tracked via an electronic “trail,” opening up a variety of privacy issues common to numerous systems
- Retention in back-end enterprise networks of information that includes sufficient personal identification to make it potentially suitable for numerous privacy-invading purposes. Examples of such back-end networks could include systems for billing and settlement, as well as systems that retain grid operational history.
- Identity theft, facilitated by misuse, or intrusion on back-end systems, communications, or the devices in the PEV.

Further research on integrating PEVs into the electric grid, as well as developing and implementing industry consensus standards, is required to realize full potential benefits64. This includes:

- **Physical grid equipment**, primarily at the distribution level. Experimental work may be needed to establish sizing and implementation guidelines.
- **Sensors** for PEV monitoring, for both charging and discharging the PEV back into the grid, along with supporting regulations
- **Controls** that allow the utility (in addition to the customer), under an agreed-to contract, to start and stop charging the PEV.
- Security of communications to and from any PEV and/or charging station
- **Modeling and forecasting** electrical demand with the increase in PEVs, and other distributed energy resources.
- **Garaging PEVs** – Research on where PEVs are likely to be garaged, both during the day and at night.
- **Natural disasters** – Using PEV batteries to support electric needs during natural disasters

PG&E’s EV Smart Charging Pilot, July 2017; https://www.pgecurrents.com/wp-content/uploads/2017/06/PGE-BMW-iChargeForward-Final-Report.pdf

64 *See for example Energy Storage Opportunities and Research Needs*, IEEE PES,June 2020; https://resourcecenter.ieee-pes.org/technical-publications/white-paper/PES_TP_WP_ESORN_063020.html,

Power Electronics and Electric Motor R&D

Successfully introducing electric drive vehicles into the marketplace is a consequence of the convergence of technological advances in materials, semiconductor devices, power electronics, controls, and batteries. For example, the technical feasibility of HEVs is primarily due to advances in power electronics and electric motors. The power electronics and electric motors that make up vehicles' electric drive systems are essential to electrified vehicles — and indeed, all of transportation electrification. As such, improvements in these technologies (components and systems) can substantially improve efficiency, reduce vehicle weight, reduce petroleum consumption, and help meet economic, environmental and energy security goals. For example, researchers in unified converter design have estimated that cost and weight of power electronics for PEVs could be cut in half or more, with aggressive development and deployment of that technology. Other new options may be just as important, and compatible with unified design.

Power electronics, controls and the electric motor are significant systems cost components, as well as technical enablers. A specific percentage of total costs is difficult to construct, as costs have been a moving target. Much of this data is also business sensitive and proprietary and varies with the different categories of vehicles — HEV, PHEV and BEV — as the battery changes in size from ~1 kWh to perhaps 100 kWh. ***For today's PHEV, the power electronics and electric motor probably contribute costs greater than the battery, while the battery certainly dominates the cost in a BEV with substantial range***.

Achievement of substantially reduced weight, volume and cost of power electronics, and electric motors, would accelerate progress in this area. Specifically, improvements are needed in the following areas:

- Reductions in weight, volume and costs of complete systems
- More efficient power electronic interfaces, and integration with electric motors, protection and control systems
- Semiconductor materials and improved device performance
- Advanced power electronics packaging and thermal management systems
- Enhanced device and power electronic system reliability
- Alternatives to rare-earth permanent magnet materials and continued improvement in electric motor performance

CONCLUSIONS

Electrified transportation is an obvious technology path to diversifying transportation energy sources. The infrastructure for electric transportation is in place, and reliance on electricity for transportation comes with numerous attendant benefits, such as:

- Increased transportation energy efficiency
- Reduced urban smog
- Reduced greenhouse gas emissions

Achieving significant penetration of these technologies requires a sustained effort--one aimed at resolving a number of research, engineering and business issues. One of the most significant needs is developing less expensive, higher performance batteries.

LIST OF ACRONYMS

BEV	Battery Electric-Only Vehicles
CO2	Carbon Dioxide
EISA	Energy Information and Security Act
EPRI	Electric Power Research Institute
EV	Electric Vehicle
FERC	Federal Energy Regulatory Commission
FFV	Flexible Fuel Vehicle
GM	General Motors
HDV	Heavy-Duty Vehicles--primarily freight trucks, buses
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt Hour
LDV	Light-Duty Vehicles
NIST	National Institute of Standards and Technology
NOx	Nitrous Oxides
NREL	National Renewable Energy Laboratory
OECD	Organization for Economic Cooperation and Development
PEV	Plug-in Electric Vehicles (includes PHEV)
PHEV	Plug-In Hybrid Electric Vehicles
PUC	Public Utility Commission
R&D	Research and Development
RFS	Renewable Fuels Standards
SUV	Sport Utility Vehicle
TEC	IEEE Transportation Electrification Community

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