



# 2011

## Vehicle Electrification: Status and Issues

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5/31/2011

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**Abstract**—Concern for the environment and energy security is changing the way we think about energy. Grid-enabled passenger vehicles, like electric vehicles (EV) and plug-in hybrid electric vehicles (PHEV) can help address environmental and energy issues. Automakers have recognized that electric drive vehicles are critical to the future of the industry. However, some challenges exist to greater adoption: the perception of cost, EV range, access to charging, potential impacts to the grid, and lack of public awareness about the availability and practicality of these vehicles. Although the current initial price for EV's is higher, their operating costs are lower. Policies that reduce the total cost of ownership of EVs and PHEVs, compared to conventional internal combustion engine (ICE) vehicles, will lead to faster market penetration. Greater access to charging infrastructure will also accelerate public adoption. Smart grid technology will optimize the vehicle integration with the grid, allowing intelligent and efficient use of energy. By coordinating efforts and using a systems perspective, the advantages of EVs and PHEVs can be achieved using the least resources. This paper analyzes these factors, their rate of acceleration and how they may synergistically align for the electrification of vehicles.

**Index Terms**— Road vehicle electric propulsion, batteries, electric vehicle charging infrastructure, climate change.

## I. INTRODUCTION

THERE are numerous factors which are coming together to change the way we think about energy [1]- [4]. There are growing concerns over energy security [5], and our dependence on foreign oil/petroleum [6]. The worldwide use of energy is growing, creating greater demand, but the supply is limited [7]. The oil that is available is becoming harder and more dangerous to extract [8], [9] as evidenced by the catastrophic Deepwater Horizon oil spill [10]- [13]. The result is that nations around the world have come to realize that action must be taken to reduce our use of oil and to reduce our greenhouse gas (GHG) emissions [14].

The mounting effects of climate change have become even more apparent, prompting action locally and globally [15], [16]. The United States has pledged to reduce greenhouse gas emissions by approximately 17 percent by 2020 [17], contingent upon climate change and energy legislation being

passed by Congress [18], a lengthy and uncertain process. On national and international levels, efforts have begun: 188 countries have ratified the Kyoto Protocol [19] and there are many signatories with emission pledges [20], [21] in the Copenhagen Accord [22] and the Cancun Agreements are a step forward [23].

In order for the U.S. to achieve the commitments [17], [24] it made in The Copenhagen Accord, significant steps must be taken to reduce our use of energy from fossil fuels [25], [26]. One of the most promising ways to do this is the electrification of transportation [27]. Up until now, the energy to power the transportation sector has come almost exclusively from oil [28]-[30]. With the electrification of transportation, all sources of electricity can be used for transportation. This marks the largest disruption in the automotive industry since its choice of the internal combustion engine [31]. Now, we can choose to use renewable sources of energy, to “fuel” our nation’s vehicles. Because of this link between EVs and electric power’s carbon footprint, regulators will have a new tool to reshape the overall way we generate and use energy. This will have profound and lasting effects – not only our nation’s power industry, but also beyond the transportation sector, affecting our overall use of the world’s resources [32].

In order to realize the cost/benefit tradeoffs of grid-enabled vehicles, it is important to take a systems perspective. The analysis in this paper identifies certain areas which must be addressed in order to achieve widespread adoption. A systems approach prevents any one area from becoming the rate-limiting step, slowing the overall adoption rate. By addressing the different, interrelated elements, it is possible to maximize the functionality of the entire system, at the minimum cost and time, while making the most efficient use of energy.

## II. GRID-ENABLED VEHICLES

Grid-enabled vehicles (GEV), such as electric vehicles (EVs) and plug-in (PHEVs) can help address environmental and energy issues, as well as provide other benefits. By using electricity rather than petroleum, EVs and PHEVs reduce our petroleum use. Overall, from well to wheels, GEVs reduce the energy consumption and emissions in the transportation sector. The emissions benefit varies based on the generation mix for that region as shown in Table I (projected for year 2020.)

Based on this projection, even in coal-intensive regions of the country, PHEVs have lower emissions compared to conventional ICE vehicles. Life cycle assessment (LCA) quantifies the environmental impacts of a product’s manufacture, use, and end-of-life. One recent study from Carnegie Mellon University [42] assessed life cycle GHG

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TABLE I  
MIX OF SOURCES FOR AVERAGE ELECTRIC GENERATION  
AMONG REGIONS IN THE UNITED STATES

Region	Coal	Oil	Natural Gas	Nuclear	Other
1. East Central Area Reliability Coordination Agreement (ECAR)	83.9	0.5	5.7	9.0	0.9
2. Electric Reliability Council of Texas (ERCOT)	45.2	0.5	37.3	11.9	5.1
3. Mid-Atlantic Area Council (MAAC)	44.1	1.2	5.5	34.2	15.0
4. Mid-America Interconnected Network (MAIN)	52.9	0.3	4.2	31.8	10.8
5. Mid-Continent Area Power Pool (MAPP)	73.1	0.4	1.8	12.3	12.4
6. Northeast Power Coordinating Council / NY (NPCC-NY)	12.3	5.6	33.9	29.3	18.9
7. Northeast Power Coordinating Council / NE (NPCC-NE)	17.5	1.8	43.0	21.9	15.8
8. Florida Reliability Coordinating Council (FRCC)	53.9	5.5	26.3	11.9	2.4
9. Southeastern Electric Reliability Corporation (SERC)	49.9	0.6	11.9	33.0	4.6
10. Southwest Power Pool (SPP)	74.1	0.6	15.9	4.3	5.1
11. Western Electricity Coordinating Council / Northwest Power Pool Area (WECC-NW)	28.8	0.1	6.4	3.2	61.5
12. Western Electricity Coordinating Council / Rocky Mountain and AZ-NM-Southern NV Power Area (WECC-RMP/ANM)	60.8	0.4	21.2	8.0	9.6
13. Western Electricity Coordinating Council / California (WECC-CA)	13.0	0.0	40.4	17.3	29.3

Percentages are for year 2020. Source: EIA 2008 from [163] used with permission.

emissions from PHEVs including energy use and GHG emissions from battery production.

They analyzed how changes in the electricity mix, vehicle efficiencies, battery characteristics, and biofuel use affect the life cycle GHGs. These researchers found that PHEVs reduce GHG emissions by 32% compared to conventional vehicles. Even with coal-generated electricity, the life cycle greenhouse gas emissions are lower for PHEVs than conventional, ICE vehicles. They also estimated that GHGs associated with lithium-ion battery materials and production account for 2–5% of life cycle emissions from PHEVs. Even with the average U.S. carbon intensity for electricity generation, PHEVs have a lower life cycle GHG than Hybrid Electric Vehicles (HEVs). However, with cleaner electricity generation, the GHG savings would become even greater.

Researchers at the Electric Power Research Institute (EPRI) with the Natural Resources Defense Council (NRDC) came to a similar conclusion [33] when conducting a wells-to-wheels analysis. In all cases of PHEV fleet penetration, and across all carbon intensity scenarios, emission levels were reduced. If the electricity is generated from renewable sources, the life-cycle GHG emissions from EVs are even lower.

Automakers around the world have recognized that the market for grid enabled vehicles will grow in coming years, with dozens of PHEVs and EVs, across a wide range of vehicle types, slated for production with many coming out by

TABLE II  
ANNUAL GREENHOUSE GAS EMISSIONS REDUCTIONS  
FROM PHEVs IN THE YEAR 2050

2050 Annual GHG Reduction (million metric tons)		Electric Sector CO <sub>2</sub> Intensity		
PHEV Fleet Penetration	Low	High	Medium	Low
		163	177	193
		394	468	478
		474	517	612

Results are for three power generation scenarios by three PHEV fleet penetration scenarios. From [33], used with permission.

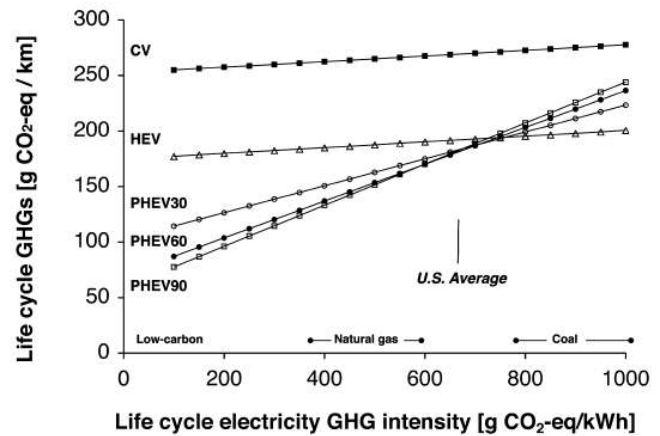


Fig. 1. Life cycle GHG emissions from vehicles shown as a function of the life cycle GHG intensity of electricity used during production [162]. The chart indicates which generation options correspond to various GHG intensities to provide some insight into generation mixes. Used with permission.

2012. Each automaker has different strategies on how to reduce cost and other market barriers and how to get their vehicles on the streets faster. Automakers' initial vehicles are an indication of what architecture and product they think consumers will want – EV vs. Extended Range Electric Vehicle (E-REV) vs. HEV. It is also a reflection of their current position and their strategies build upon their strengths.

Toyota, for example is the leader in HEVs using nickel metal hydride (NiMH) batteries, but it has been widely reported [34] that their engineers picked the wrong chemistry (nickel-cobalt based Li ion) which has delayed their PHEV and EV development, but with the electric RAV4 and Lexus RX being developed in partnership with Tesla, the situation may change [35].

GM believes that range anxiety is a key challenge, perhaps based on their prior experience with the EV-1 [36], [37]. E-REV architecture is more expensive [38], given the fact that it has the electric drive train (battery, electric motors) plus a fuel-burning generator/engine. Nissan is using its vertical integration [39] and is making a significant investment in EVs, in order to bring costs down faster than its competitors. Nissan has taken first mover's advantage in the USA with the Leaf, a reasonably priced, all electric "Zero Emissions Vehicle."

TABLE III  
TOTAL COST OF OWNERSHIP

One-Time Costs/Revenue		Total Recurring Costs	Total Recurring Revenue
(base price - rebates	+ road-years x	( maintenance costs	+ ( V2G revenue + V2B savings))
+ sales tax - sales tax offset		+ parts disposal costs	
- resale/salvage value		+ vehicle tax - vehicle tax offset	
+ charger cost - rebates		+ registration - registration offset	
+ charger installation - rebates)		+ inspection - inspection offset	
		+ insurance - insurance offset	
		+ finance - finance offset	
		+ parking - parking offset	
		+ tolls - toll offset	
		+ yearly car washes	
		+ yearly accessories	
		+ fuel costs	
		+ fed fuel tax	
		+ state fuel tax)	

The terms in red indicate possible ways to incentivize the adoption of grid-enabled vehicles.

BYD has less experience, but more to gain, and is pursuing EVs partly due to the simpler engineering. The Chinese battery manufacturer and automaker also is taking advantage of vertical integration and is not bound by legal and liability constraints that other manufacturers face. The lower requirements of the domestic Chinese market, and less danger in hurting their brand, allow BYD to be more aggressive than traditional automakers.

Upstarts, like Fisker and Tesla, are introducing high-performance sports cars for the luxury performance market initially, with plans to pursue the broader, mainstream market in their second vehicle [40]. Although these automakers have different approaches, all share a common perspective: electric drive vehicles are critical to the future of the auto industry. They also realize a common critical aspect of the EV's success is to have smart systems that enable the vehicle to better communicate with their owners, the charging stations and the utilities. By the end of 2011, industry observers predict there will be tens of thousands of EV on the streets, in 2012 – hundreds of thousands, and by 2020, the global Electric Vehicle Initiative has set targets of 20 million [41]. For an updated list of grid-enabled vehicles (GEVs), see the information we have compiled here [42].

A locus for adoption of GEVs will be fleets. Fleet vehicles – city police, garbage, street cleaning, buses, delivery vehicles, etc. are likely to be an accelerator of EV adoption broadly. For the United States, there were 16 million fleet vehicles on the road in 2009 [43]. Fleets offer many advantages [43]:

- Fleet operators understand total cost of ownership (see Section III).
- The cumulative effect of tax credits for EVs in a fleet are attractive.
- Routes are predictable and short. Utilization rates of fleet vehicles are high.
- Fleets use centralized parking areas that also may present the option of a renewable energy park/charge.
- EVs have low maintenance which is especially attractive to fleet operators. Commercial power rates for fleets are lower than residential.
- Fleets offers access to more financial instruments to

finance the initial high costs for EVs.

- EVs in fleets can help meet corporate greening goals.

GE will purchase 25,000 EVs by 2015 for its own fleet and for others managed through its Capital Fleet Services [44]. The auto rental companies with large fleets such as Enterprise, Avis, and Hertz's adoption will help make the GEV drive experience accessible to the public consumer with programs like Hertz Connect [45], [46]. Likewise the public consumer will experience the GEV drive experience with Taxi fleets including several cities in Japan [47], Shenzhen China [48], and the San Francisco Bay Area in the United States [49]. The American Recovery and Reinvestment Act of 2009 directs the General Services Administration (GSA) to spend \$300 million for hybrids, plug-in hybrids or electric vehicles by Sept. 30, 2011 [51]. The Administration also issued Executive Order 13514 signed on October 5, 2009 that sets government-wide efficiency and emissions goals and reasserts a prior Executive Order, 13423, issued in 2007 to purchase commercially available plug-in vehicles [52]. These orders state the goal of reducing petroleum consumption in agency fleets of 20 vehicles or more by 2% annually, through fiscal year 2020, relative to a fiscal year 2005 baseline. For 2011, the GSA plans an initial purchase of 100 PHEVs [53].

### III. CHALLENGES

In order for grid-enabled vehicles to achieve their potential, however, many challenges must be addressed including: cost, EV range, charging access and infrastructure, impact to the grid, and consumers' lack of awareness of the EV option and trade-offs.

#### A. Cost

Perception of cost is a challenge. Consumers tend to focus on initial cost, not total cost of ownership, when making purchasing decisions. Apart from sticker price and a vehicle's gas mileage, few consider other factors, such as rebates, incentives, operating and maintenance costs, when comparing vehicles. Furthermore, many consumers sell or trade-in their

vehicles after a few years, which may be shorter than the payback period for an EV or PHEV.

### 1) One-time costs

The biggest drivers for one-time costs are the cost of the battery, rebates, disposal costs, and resale or salvage value. The total cost of ownership is summarized in the schematic equation in Table III. The equation has three parts – one-time costs and revenue, recurring costs and recurring revenue. A vehicle will have initial costs to purchase it, onetime costs for worn parts replacement and disposal, and finally resale or salvage value at the end of ownership. Grid-enabled vehicles will also have a cost for the charging equipment. A car will have many recurring costs over its lifetime, shown in the middle of the equation. Finally for grid-enabled vehicles there are revenue and/or savings from vehicle-to-grid (V2G) or smart charging (V1G) or vehicle to building (V2B) programs. The terms in red indicate possible ways to incentivize the adoption of grid-enabled vehicles.

There have been comparative studies of ICE and battery hybrid electric vehicles (BHEV), and battery electric vehicles (BEV) lifecycle costs structured like Table III – for example the UC Davis Institute for Transportation Studies group analyzed census data of the different costs for EVs and ICEs [54], [55]. However these studies are dated and an updated analysis would be timely.

Governments around the world are using rebates to reduce the initial cost of EVs and PHEVs and to encourage their adoption. The current federal rebate for EVs and PHEVs in the U.S. ranges from \$2500 to \$7500, depending on the size of the battery. This rebate applies to the first 200,000 vehicles made by each automaker. In addition, some states [56] have established rebates of up to \$5000. China has a pilot subsidy program [57] which reduces the cost of EVs by 60,000 RMB (US\$8800) and PHEVs by 50,000 RMB (US\$7320.)

The industry consensus is that battery costs will come down from current costs of \$1000-1100/kWh to below \$500/kWh in the next few years (see Fig. 2.) [58]- [61]. It should be noted that most discussions of cost use the nameplate energy of the battery. This metric can be deceptive, however, as many automakers only use a portion of the battery's total energy during vehicle usage. Thus, the usable energy can be significantly less than the total energy. For example, GM's Chevy Volt 16 kWh battery is programmed to use only uses 8 to 8.8kWh, or 50-55% of the total energy in the battery. There are several reasons why an automaker might limit the usable range of the battery. Most batteries lose power as they are discharged. Thus, at low States Of Charge (SOC) they are unable to meet the vehicle requirements. In order to maintain vehicle function, the automaker can set the lower limit of battery operation, to ensure that the driver has the same power (acceleration) regardless of whether the battery is fully charged or mostly depleted. Automakers might limit the battery from being fully charged to 100% SOC in order to enhance the battery's safety. Some chemistries, notably the metal oxide variants, are more likely to experience safety issues when fully-charged. In addition, some chemistries do not cycle as well as others. In order to extend cycle life, the SOC range may be reduced. As automakers gain more experience and as technology improves, it is likely they will

move to batteries that allow a higher percentage of usable energy, as this would allow the same range to be achieved in a smaller, lighter, less expensive battery.

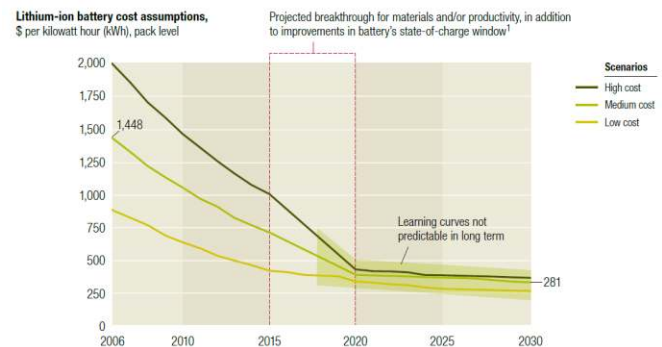


Fig. 2. Battery costs are projected to come down from current costs of \$1000-1100/kWh to below \$500/kWh in the next few years. Used with permission, from [58].

Rare earth metals are a factor contributing to electric vehicle cost. Samarium-cobalt or neodymium (terbium and dysprosium are added in smaller amounts) rare earth magnets are used in motors of electric vehicles. In addition, nickel metal hydride (NiMH) batteries (used in the Prius for example) require significant amounts of the rare earth lanthanum, which is one of the reasons why automakers are moving to lithium ion batteries instead of NiMH. Each electric Prius motor requires 1 kilogram (2.2 lb) of neodymium, and each nickel metal-hydride battery uses 10 to 15 kg (22-33 lb) of lanthanum [62]. In addition, a major consumer of rare earths is the wind turbine industry [63] thus exacerbating the whole supply issue.

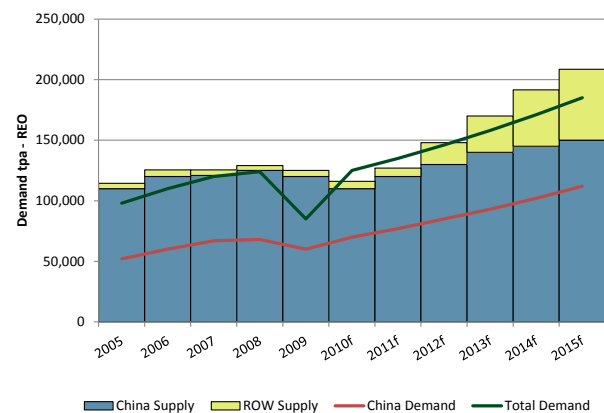


Fig. 3. "Dudley" Chart of projected rare earth ore demand. Source IMCOA, Roskill, CREIC, and Rare Earths Industry Stakeholders. From [66] with permission.

Rare earths, despite their name, are not especially rare. The problem is finding ore bodies that have enough concentration to exploit. China plays a big role in the geopolitics of rare earth supply. One mine in the USA, the Mountain Pass Mine in California was at one time the leading supplier in the world of rare earths until 2002 when China undercut them and Mountain Pass shut down operations.

Recently, China, which now controls 93% of worldwide production, has made moves to put limits on production and export of rare earths as a strategic step by the Ministry of Industry and Information Technology, and this is to ensure China's own internal supply, so it can gain an edge in EV and other green technologies for its own internal use and export. It has been reducing the export quotas for the last 3 years [64]. In response to potential supply disruptions, MolyCorp Minerals, LLC which now owns the Mountain Pass Mine plans to restart operations [65].

Dudley Kingsnorth of Industrial Minerals Company of Australia (IMCOA) has updated and produced a graph on rare earth demand and supply, known as the "Dudley Chart" in the rare earth commodity community, shown in Fig. 3. The analysis behind this graph indicates that rare earth mining capacity will be tight up to 2015 [66]. This is likely to keep rare earth costs high. Perhaps most significantly, the analysis forecasts the demands for Neodymium, Europium, Terbium, and Dysprosium are in ranges that could outstrip supply by 2015.

The US Department of Energy (DOE) is pursuing a strategic plan for rare earths (and other important elements including lithium, cobalt, indium, and tellurium.). This was announced in a March 17, 2010 speech, by Assistant Secretary of Energy for Policy & International Affairs David Sandalow [67]. Since then, there have been multiple testimonies to congress and the Critical Materials Strategy was released on December 15, 2010 [68]. The analysis in this strategy report considers a scenario where Neodymium is forecasted to outstrip supply by 2015. Furthermore, the study's most conservative scenario still forecasts demand to outstrip supply by 2020.

Various articles and reports have discussed potential shortfalls in lithium production vs. expected demand and tried to navigate the future geopolitical and socioeconomic implications of lithium [69]- [72]. Lithium has been likened to oil, and Chile or Bolivia or Afghanistan [73] have all been described as the "Saudi Arabia for lithium." Salar de Uyuni, the world largest salt flat made Bolivia the number one pick for the title [74] until new news of a wealth of mineral reserves in Afghanistan made the news [75]. The world's second largest salt flat, Salar de Atacama, has also given Chile the same title [76].

Although there has been much talk about lithium, numerous studies indicate that concern over lithium availability is unfounded [77]. Table IV summarizes the lithium reserves from the various producing countries. To compare reserves against consumption, the 24kWh battery for the Nissan Leaf will use 4kg of lithium (metal equivalent) [70]. If the entire world's known lithium reserves were used for battery production, there would be enough lithium for hundreds of millions of Leaf-sized batteries, even without considering recycling and more expensive forms of lithium extraction.

Researchers at Argonne National Labs studied the expected demand for lithium, taking into account lithium ion batteries for transportation [78]. They compared the total expected demand with estimates of production, known reserves, and the quantity of lithium that could be recovered by recycling. They concluded: "Even by using the U.S. Geological Survey's (USGS's) conservative estimates of lithium reserves, the available material will not be depleted in the foreseeable future." In addition, they added, "Bottom line: Known lithium reserves could meet world demand to 2050." Furthermore, lithium is not a major component of lithium ion batteries' cost and is not a significant concern.

There are paths to harvesting lithium other than exploiting existing sources, such as salt flats. Lithium can be extracted (at greater expense) from spodumene and other pegamatic minerals such as, lepidolite, petalite, amblygonite, and eucryptite [79]. One promising method, being explored by Simbol Mining, is extracting lithium from geothermal fluids [80]. Lithium could be extracted from salt water [81] – a method South Korea is exploring – but that is an expensive path [82]. There are also other sources of lithium including oilfield brines and Hectorite clays and Jaderite [83], [84].

Given that the easily-exploitable reserves of lithium and rare earths are finite, they have strategic value and thus may become resources to control in the geopolitical sphere, potentially causing shortages in the future. This is more than just a possibility; in September 2010, China temporarily cut off rare earth shipments to Japan, apparently to apply political pressure on Japan to release a Chinese trawler captain detained in a fishing zone dispute [85]. The value of commodities shift – regardless of the present surplus, if the demand becomes greater than the supply, this could pose a future challenge. Research and development on new battery technologies high performance motors, and magnets that reduce or eliminate rare earths could help us hedge our bets [86], [87].

TABLE IV  
WORLD LITHIUM PRODUCTION AND RESERVES (2005)

Country	2005 Production (tonnes)	Reserves (tonnes)	Reserve Base (tonnes)
United States	1,700 (MIR)	38,000	410,000
Argentina	2,000	1,000,000 (MIR)	2,000,000 (MIR)
Australia	2,240 (MIR)	160,000	260,000
Bolivia	-	2,700,000 (MIR)	5,400,000
Brazil	240	190,000	910,000
Canada	700	180,000	360,000
Chile	8,000	1,500,000 (MIR)	3,000,000
China	2,700	1,100,000 (MIR)	2,700,000 (MIR)
Portugal	320	NA	NA
Russia	2,200	NA	NA
Zimbabwe	240	23,000	27,000
TOTAL	20,340	6.8M	15.0M

Source USGS and Meridian International Research. From [69] with permission.

## 2) Recurring costs

When comparing grid-enabled vehicles with conventional ICE vehicles, the differences in recurring costs are largely due to operating and maintenance expenses. (Rebates and incentives may be significant for a while, but will in all likelihood be eventually phased out.) When estimating operating costs, powering a vehicle using electricity is significantly cheaper than powering it using fossil fuels. An EPRI study [88] estimated the equivalent cost of powering a PHEV on electricity as 75 cents per gallon of gas, assuming an average cost of electricity of 8.5 cents per kilowatt hour and an average fuel economy of 25 miles per gallon.

In order to improve air quality (and to be good global citizens) many cities and local governments offer offsets for

recurring costs to incentivize the purchase of EVs. Some cities exempt electric vehicles from parking charges or fees, for example London's scheme that exempts electric vehicles from the congestion pricing tolls [89]. Other countries have imposed large registration fees or taxes on purchases of traditional ICE vehicles, while exempting electric vehicles. Israel and Denmark provide two notable examples.

### 3) *Recurring revenue*

With the possibility of vehicle batteries connected to the grid, new business models are beginning to emerge, with different concepts on how to monetize this distributed energy storage resource. Most vehicles are used for transportation an hour or two a day. The rest of the time, that expensive asset sits idle. If the battery can be used for grid services without compromising its value to power the vehicle, it may be a potential revenue stream. The ability to use EVs and PHEVs as a resource depends on appropriate support infrastructure, as well as the existence of aggregators and customers who are willing to provide the service. The initial use of vehicles for grid services will occur in areas that require the lowest infrastructure investment. Aggregators will use the existing charging infrastructure, combined with communications systems, to aggregate many vehicles and offer services. Unidirectional (one-way) power flow can be modulated, the charging of the vehicle can be slowed, stopped, giving rise to services such as demand response, and emergency load curtailment. The revenue from these services would presumably be split between the aggregator and the vehicle owner [90].

If technical and regulatory hurdles can be addressed, it may also be possible to have bidirectional power flow, meaning that power can flow from a vehicle to the grid. V2G services that might be offered by vehicle batteries include load leveling or other forms of arbitrage, ancillary services such as frequency regulation and spinning reserve, and backup power in the event of power outages.

One primary concern regarding the use of vehicle batteries for grid services is the impact on battery life. A study from Carnegie Mellon concluded that a PHEV pack made of lithium iron phosphate cells would incur little capacity loss from combining (V2G) activities with regular driving [91]. It is not clear whether other lithium ion chemistries would show similarly positive results. The University of Delaware has several groups working on grid-integrated vehicles and vehicle-to-grid power. Professor Willett Kempton and his group have written extensively on this topic, projecting that the value of offering these services could total thousands of dollars over the life of the vehicle [92]. Federal Energy Regulatory Commission (FERC) Commissioner Jon Wellinghof has also spoken in support of the "cash back hybrid" [93]. Nonetheless, the economics and practical viability of V2G services remains a topic of debate [94].

### 4) *Hidden costs*

Certain costs in vehicle ownership are hidden. Specifically, environmental and societal costs are not explicitly built into the price of fuel. Various mechanisms have been proposed to capture these hidden costs, particularly the costs incurred by society for carbon emissions. If these costs could be explicitly

factored into the recurring costs of vehicles, the total cost of ownership would be significantly different than today's out-of-pocket costs paid by vehicle owners.

The U.S. is critically dependent on petroleum, consuming more than any other nation in the world. In 2009, the U.S. consumed 21.7% of the oil produced worldwide. Oil provided 39% of the U.S. primary energy needs in 2009 [95]. Much of this oil is used for the transportation sector, which relies on oil for 94% of the fuel used. The world economy would be severely impacted if oil production and delivery were to be disrupted. In fact, every major recession in the U.S. over the past 35 years has been preceded by, or was coincident with, an oil price spike [96]. In order to maintain the flow of oil, the U.S. must spend many tens of billions of dollars each year. The Rand Corporation estimated that the U.S. might be able to save between 12 and 15% of the fiscal year 2008 U.S. defense budget if all concerns for securing oil from the Persian Gulf were to disappear [97]. In addition, the volatility in energy prices restrains economic activity, as businesses and consumers delay purchasing decisions when oil prices increase.

When discussing cost of electrifying transportation, it may be equally valid to discuss the cost of NOT electrifying transportation. As a society, if we do not substitute renewable for non-renewable sources of power – which can be accelerated by electrifying transportation – we will continue to spend hundreds of billions securing the flow of oil, plus more on the oil itself. We will also continue to emit CO<sub>2</sub> into the atmosphere, increasing the cost of carbon reduction strategies. Eventually, it is likely that CO<sub>2</sub> levels will reach a point where climate change is irreversible. In that instance, the cost of CO<sub>2</sub> reduction is irrelevant because no amount of money and time can solve the problem. Thus, any systems analysis regarding the cost of vehicle electrification should incorporate the hidden costs to taxpayers to maintain the current energy production and delivery system, to avert climate catastrophe, and the costs if climate catastrophe is not averted.

### B. *EV Range*

EV range is the second most significant barrier to wider EV adoption. The fear of being stranded due to a depleted battery has been termed "range anxiety." Conventional vehicles can be fueled at gas stations which are plentiful. Thus drivers need not plan their refueling far in advance. Currently, opportunities for Level 2 charging are limited as opposed to Level 1 charging. Efforts are underway to change this with Level 2 and a few Level 3 charger deployments in DOE sponsored programs. Although 110V outlets are widely available, the relatively low charging rate at 110V means that even after one hour of charging, one would only have added four or five miles of driving range [98].

The actual range required for the vast majority of trips can be covered by most EVs. Fig. 4 is data taken from the 1995 National Personal Transportation Survey (NPTS) [99] showing the daily driving distance distribution and the resulting utility factor, which is the fraction of total daily VMT that are less than or equal to the stated distance. Half of trips are 40 miles or less and three quarters do not exceed 100 miles. (A more recent 2005 survey confirmed this data with a similar estimate for commuting of 32 miles per day [100].)

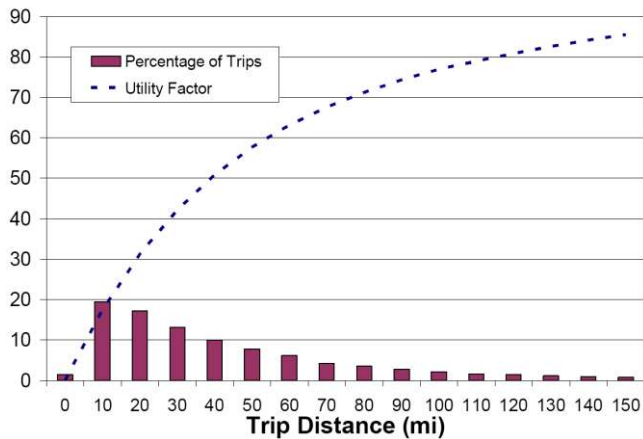


Fig. 4. The figure shows data taken from the 1995 National Personal Transportation Survey (NPTS) showing the daily driving distance distribution and the resulting utility factor, which is the fraction of total daily vehicle miles traveled (VMT) that are less than or equal to the stated distance. From [99], with permission.

Although the vast majority of trips can be covered by the typical EV, consumers often make purchase decisions based on the maximum usage, not typical usage. For example, some consumers may purchase a sports utility vehicle because they take an annual ski trip where they need the cargo space, despite the fact that in their daily usage they do not need such a large vehicle. From a systems perspective, this individual might be better off driving a smaller vehicle for daily use and renting a larger vehicle on the rare occasions when they need additional functionality. Similarly, EVs may meet all of the needs for typical daily driving, but may not be suitable in certain circumstances, such as long road trip, at least in the early years of large scale EV charging infrastructure deployment.

Electric vehicles operating in cold or hot environments will suffer from decreased range because some of the battery's energy is used to heat or cool the vehicle, rather than only to turn the wheels. Conventional ICE vehicles have an inefficient fuel-burning engine, which generates significant waste heat. In the wintertime, this waste heat is used to warm the cabin air. EVs don't have this inefficient fuel-burning engine, so the battery must be used to power a heater in an EV. In addition, other loads in the vehicle, such as a window defroster or seat heater, would drain the battery more quickly in the winter. Similarly, in hot weather, the battery must be used to run the air conditioner, reducing EV range. Although there is a small loss of battery energy at low temperatures, it is recovered when the battery is warmed during usage. In other words, the reduced driving range of EVs in cold weather is primarily due to the additional loads placed on the battery, not the inability of the battery to store or hold its charge at those temperatures. In extreme temperatures, if the vehicle is plugged in, it may be possible to preheat or precool the vehicle, to maximize EV range.

There are a few different approaches to address this challenge of EV range.

### 1) Batteries with higher energy density

Batteries are the focus of considerable development efforts since higher energy density translates to greater EV driving range. Unfortunately, there is no Moore's Law for batteries and no silver bullet is expected, despite regular announcements proclaiming some new breakthrough materials technology. Energy density and cost for consumer lithium ion batteries have improved at a fairly consistent rate of 8-10% per year, for many years [101]. Automotive batteries should improve at a faster rate initially, due to economies of scale, but will reach an asymptote. Even if energy density improves on a gravimetric or volumetric basis (Wh/kg or Wh/liter), cost still remains a key concern, since more energy-storing active materials will be required per battery. Part of the interest in iron phosphate and manganese spinel batteries is due to their potential for low cost, given their relatively inexpensive materials, while retaining good energy density.

### 2) Battery switching

One way to alleviate range anxiety is to have a network of battery switching stations. Better Place has demonstrated the capability of switching an automotive battery in less than three minutes, the amount of time it takes to fill up a gas tank [102]. In April 2010, Better Place demonstrated the world's first switchable-battery electric taxi in partnership with the Japanese government and Nihon Kotsu, Tokyo's largest taxi operator [103]. The battery switching solution works very well for certain drivers and usages, particularly those in dense urban areas with limited need for long journeys into rural locations. Battery switching is also well suited to fleet operators of commercial vehicles, where there are often central depots for vehicle storage and maintenance. It also offers that possibility of long trips for fully electric vehicles if a nationwide network of battery switching stations can be established. This in turn would require some level of standardization of batteries, so that charging stations would only have to deal with a manageable inventory of different battery types. Today particular battery technologies are seen as competitive advantages by car manufacturers, so arriving at



Fig. 5. Better Place battery switch station. Photo courtesy of Better Place

some manageable number of standards will be a challenge.

### 3) *Fast Charging*

If batteries had the ability to be “fast-charged” without impacting their life or adding significantly to the system cost, then when coupled with widespread charging infrastructure, drivers would be less prone to range anxiety. Unfortunately, virtually all lithium ion battery chemistries suffer from significantly lower life if they are subjected to fast charge, i.e. being fully-charged in less than 15 minutes. The problem is not that lithium ion batteries can’t be charged in 15 minutes or less. The problem is that battery with this fast-charge property would have the undesirable qualities of less energy (EV range), higher cost, and/or shorter life. So, fast charge might be a useful capability if you only drew upon it infrequently. However, automakers and battery manufacturers must assume that if they provide consumers with this option, there are some users who will use it each and every time they charge the vehicle. This would result in a short battery lifetime and would necessitate a costly battery replacement. In addition, designing the battery, charger, and other hardware to handle the higher power would add cost to the system.

### 4) *On-board engine or generator*

An on-board generator changes the vehicle from an EV to an extended-range EV or “E-REV”. This is the architecture of the Chevy Volt and Fisker Karma, which are touted as “no-compromise” EVs. The vehicle operates like an EV, drawing all of the power from the battery, until reaching a certain battery SOC. At this point, the generator or engine is turned on, to provide the energy to drive the vehicle and recharge that battery. The generator could take many forms: gasoline engine, diesel generator, fuel cell, turbine, or perhaps something else. If drivers do not fully deplete the battery during usage, they may never need to fill up the generator’s tank. The primary advantage is that the vehicle will never be stranded, as long as there is fuel to supplement the battery. The disadvantage is that the cost, weight and complexity of such vehicles are higher because of the need for both the electric drive train and the on-board generator. This might also mean that the maintenance cost will be higher than for a pure EV.

## C. *Access to charging*

Access to charging is another challenge that must be addressed, in order to achieve wider EV penetration. One of the challenges for EVs, at the system level, is to make a charging infrastructure available to the largest number of potential users at the minimum possible cost. In order for EVs and PHEVs to be successful, vehicle owners must have at least one reliable place to charge their vehicle. In most cases this will be their home, but it could be a parking garage or some other location. The current network of gasoline stations offers tremendous flexibility for ICE vehicles: filling stations are plentiful, pumps use standard dispensing nozzles, and different vehicles use the same forms of fuel. The electric vehicle charging infrastructure must emulate the convenience and interoperability of the existing fueling infrastructure. Fortunately, electricity is widely available and electric

vehicles will all use the same “fuel.” The challenge is delivering the electricity to a wide variety of vehicles, in many possible locations, at the minimum system cost, and with an acceptable charging time. In order to achieve the goal, a few challenges must be addressed:

- Interoperability of chargers and vehicles (standardization of communications, plugs, interfaces, and power)
- Clear regulations and standards for the installation of chargers
- Reliable access to charging infrastructure
- Availability of widespread fast charging to permit long trips.

### 1) *Infrastructure*

The rate of EV adoption will be determined by behavioral considerations concerning charging location (density), the duration of charging time, and the current challenge of mileage range of a full charge – a.k.a. range anxiety.

Potential charging stations locations include: homes, workplaces, restaurants, movie theaters, shopping centers, highway rest stops, and municipal facilities.

The National Electric Code (NEC), which covers EVs in Article 625, will have major revisions in its 2011 edition to track the much-changed EV landscape. EVs are covered Section 86 of the Canadian Electric Code. Historically, the California Air Resources Board classified levels of charging power in Title 13 of the California Code of Regulations around 1998. This was then codified in the U.S. 1999 National Electrical Code section 625. The current codification of these levels from the SAE J1772 revision ratified on January 15 2010 follows [104]:

- **AC Level 1**, On-board either 120 VAC, 1-phase 12 A rate with a 15 A Circuit or 120 VAC, 1-phase 16 A rate with a 20 A Circuit (4-6 miles for every hour of charging)
- **AC Level 2**, On-board 208 to 240 VAC, 1-phase up to and including 80 A, per NEC 625 (18-20 miles for every hour of charging)
- **DC Level 3**, Off-board (200 miles for every hour of charging) Under Development: –300-600 VDC, 240 VAC/3-Phase or 480 VAC/3-Phase 150-400 A circuits.

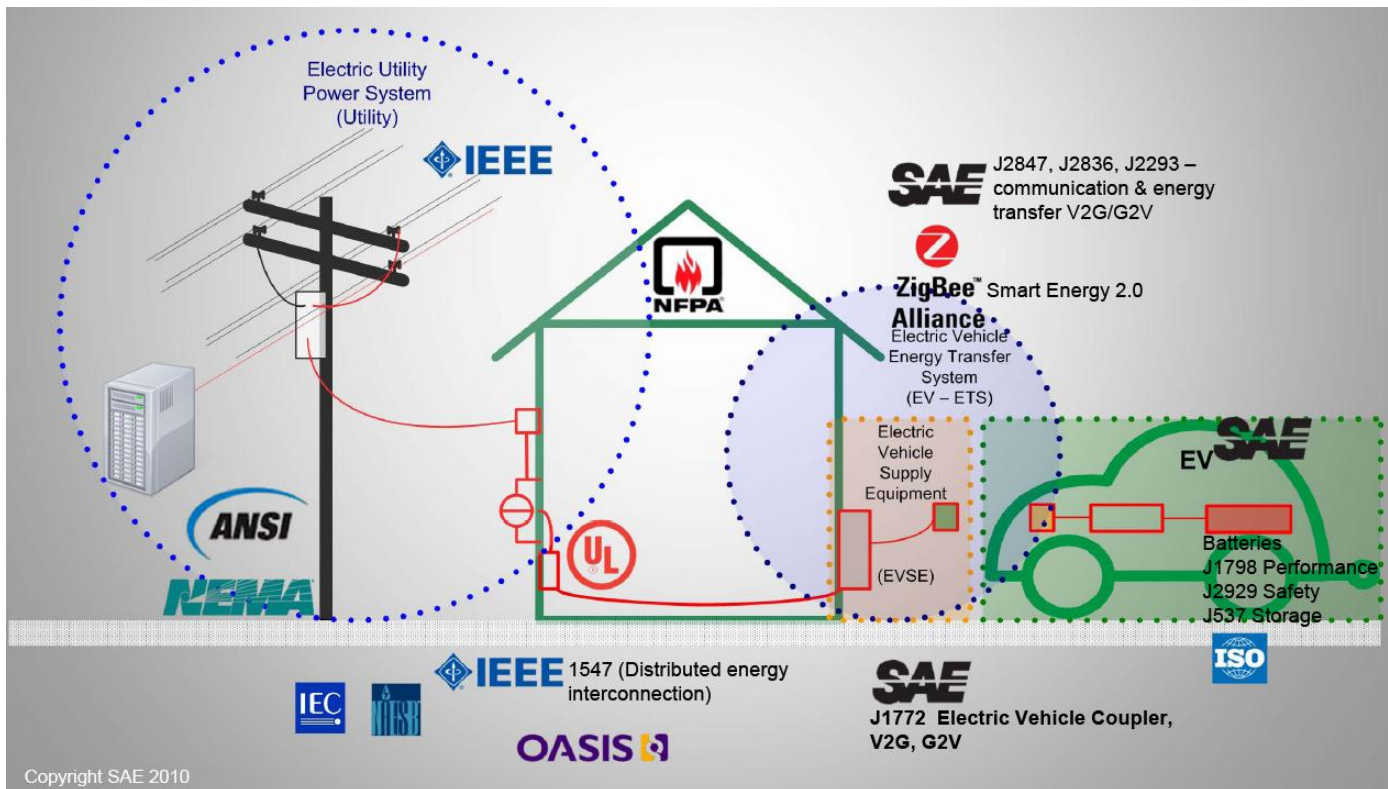


Fig. 6. Electric Vehicle Energy Transfer System nomenclature and applicable standards for an Electric Vehicle Energy Transfer System [167]. Used with permission.

Level 1 and Level 2 are considered practical for home. Level 3 (fast DC charging) will be for public or institutional charging situations. Levels 2 and 3 require a dedicated Vehicle Supply Equipment (EVSE).

For Level 2, there may be a limit to charging rate due to the charging equipment on the car. Most of the plug-in vehicles scheduled for delivery in the next few years have the electronics that convert from 120V or 240V AC to the DC voltage that actually charges their batteries on-board the car and controls the charging rate. For example the charging rate of the Chevy Volt and Nissan Leaf is limited to 3.3kW even at 240V. Limiting the charge rate to 3.3kW minimizes the on-board hardware cost. Other vehicles like the Tesla can handle considerably more power and need to, because they have considerably larger batteries.

Current standards vary by country. For example, extension cords for 240V chargers are not allowed by U.S. National Electric Code Article 625 – the charger must have its own dedicated cord. In Canada and Europe, extension cords can be used. Also for Europe, the EVSE input connections are 3 phase 240V.

Level 3 refers to DC charging, or "fast charging." There are currently no International standards for fast charging. SAE is working on a revision of SAE J1772 to include fast charging to be approved in the August 2011 time frame [105], [106]. 2010 cars, such as the Nissan Leaf, that support fast charging are using the CHAdeMO Association connector, spearheaded by the Tokyo Electric Power Company (TEPCO) [107].

Fig. 6 depicts a systems diagram for charging an EV [108]. The Energy Transfer System for Electric Vehicles (EV-ETS) is implemented by the coordination between charging infrastructure located on the car and the off-board Electric

EVSE, The EV-ETS is covered by SAE standard J2293/1 and J2293/2. Although the term "charger" is sometimes used to describe the stationary hardware the vehicle connects to, in Level 1 and Level 2 charging, the charger is located on-board the vehicle.

In article 625 of the NEC [109], the Electric Vehicle Supply Equipment is defined as "The conductors, including the ungrounded, grounded, and equipment grounding conductors, the electric vehicle connectors, attachment plugs, and all other fittings, devices, power outlets, or apparatuses installed specifically for the purpose of delivering energy from the premises wiring to the electric vehicle."

The EVSE works with the on board charger (OBC) on the car (for Level 1 & 2 charging) The EVSE contains a contactor and control circuitry. The OBC controls the charging rate and sends commands to the EVSE and the OBC will tell the EVSE to stop when the battery is fully charged. The EVSE also has Start/Stop buttons and status indicators.

A multi-car EVSE can be more complicated and includes "Smart Charging" capabilities to manage peak load by rotating the charging amongst the car being charged to limit the load to a specified level. This could also be applied to the neighborhood level to control limit the load on distribution transformers.

Benefits → Other terms		Real Time Comm. with Utility	Cheaper Fuel for Customers	Timed Charging	Back-up Power	Uni-Directional Ancillary Services (A/S)	Bi-Directional A/S	Off-Peak Load	Load Shifting for Wind Farming	
<b>V0G</b>	Convenience charging	✗	✓	✗	✗	✗	✗	✓	✗	→ <b>V0G (Convenience charging):</b> vehicle starts to charge as soon as it's plugged in, like a typical appliance
<b>Timed Charge</b>	TOU charging	✗	✓+	✓	✗	✗	✗	✓	✗	→ <b>Timed Charge:</b> vehicle doesn't charge until a given time (from an installed program or a signal from the utility) when rates and grid load are low
<b>V1G</b>	Smart charging	✓	✓	✓	✗	✓+	✗	✓	✗	→ <b>V1G (Smart Charging):</b> vehicle communicates with the grid in real time, and charges exactly when the grid needs it to. The vehicle also can provide ancillary services for extra revenue
<b>V2B</b>	V2Home	✗	✓+	✓	✓	✗	✗	✓	✓	→ <b>V2B (Vehicle-to-Building):</b> Like V2G, except the electrified vehicle does NOT communicate with the grid but instead with an individual building's energy management system. No ancillary services.
<b>V2G</b>		✓	✓+	✓	✓	✓	✓	✓	✓	→ <b>V2G (Vehicle-to-Grid):</b> Like V1G, except the car can discharge, allowing a wider range of grid services as well as storage and back-up power
<b>V2G NGU</b>		✓	✓+	✓	✓	✓+	✓+	✓	✓	→ <b>V2G NGU:</b> V2G but in the future, when the grid has become smarter and more reliant on renewables, efficiency, etc.

Fig. 7. Rocky Mountain Institute's Dichotomy of charging flavors. Used with permission from [110].

In order to promote EV adoption, the user experience must be streamlined from the auto dealership to the installation of EVSE and interaction with the local utility. Finding qualified installers of EVSE may be a problem, as this is a new area. Another potential issue is the lack of standards for the installation of EVSE. Inspection is a local issue and inspectors rightly need to ensure safety after electrical work is done. If an inspector is not given clear guidelines on what is acceptable, there may be reluctance to approve EVSE installations. Since early adopters will be the first to install EVSE, they may experience unwanted delays in getting EVSE installed and certified. Poor user experience from otherwise enthusiastic early adopters may dampen desire from others.

For homeowners or apartment dwellers who have a dedicated parking spot, the cost of installing the charger or outlet will depend on each individual situation, but is estimated to range from \$500 to \$2500 for a Level 2 EVSE installation. To lessen the costs in the future, building codes could be modified to require that 220 V outlets or conduits be installed in garages. This price is high but is expected to come down with economies of scale. Governments around the world have funded programs to seed charging infrastructure deployment and these programs will help accelerate the realization of these economies of scale.

There are various flavors to charging [110]. The flavors follow an order of complexity as shown in Fig. 7. V0G is the simplest – you plug the car in and it charges. Vehicle to Grid is the most complex as it entails putting power from the batteries back onto the grid. This involves net metering and the right business models. The ability to minimize negative impact to the grid from electric vehicles is one of the reasons why utilities are anxious to integrate smart charging capability.

V1G or smart charging refers to a variety of technologies that involve grid-enabled vehicles interacting with the electrical grid beyond simple charging. Home Area Networks

or HANs generally supply the local 'smarts' for V1G and enable the utility to use the batteries as a distributed resource via the HAN's interface to the utility. Smart charging could involve time-of-use rates, demand response programs, critical peak pricing, and charger load shaping to maximize capture of renewable generation.

Vehicle to Building/Home (V2B/V2H) use provides some of the benefits of V2G, only locally with the building energy management system.

Interoperability is needed not only at the physical level of connector but also in the handshaking and communications between the electric vehicle, EVSE, HAN, advanced metering infrastructure (AMI), and the smart grid. There are two interrelated SAE standards concerning this: J2836 - Recommended Practice for Communication between Plug-in Vehicles and the Utility Grid and J2847 – Information Report for Use Cases for J2836 [111].

There is also an alliance, The Smart Energy Profile (SEP) Alliance [112] that created the Smart Energy Profile v2.0 [113]. The alliance is creating an application layer standard to specify how smart appliances, including grid-enabled vehicles, will communicate with utilities and other grid service providers. This alliance is like the USB Alliance in that they will certify a device – in this case a grid-enabled vehicle – is compatible with products from other members in the alliance. This group grew out of the Zigbee Alliance and HAN protocol work surrounding AMI.

## 2) Ramp-Up of Charging Programs

EV charging stations, including ones using renewable energy, do exist now in several major cities such as New York [114], Los Angeles, Chicago [115], and Copenhagen. The existence of these stations is largely unknown to the public and one of the key challenges for EV adoption is public awareness and perception. Much like the adoption of mobile devices [116], the adoption of EVs should be greatly accelerated as more users embrace the technology.

Many parties are competing to develop and deploy charging infrastructure. Even with standards on charger plugs, communication and security protocols, there are many opportunities to generate and license intellectual property. Since automakers, charging infrastructure companies, governmental agencies and organizations all have an interest in developing the EV market, partnerships are being formed to deploy hardware. From companies such as McDonald's to local municipalities, there are many kinds of parties interested in installing chargers. They are making deals with charging companies or are partners for grants [117], [118].

Both Coulomb Technologies (ChargePoint America) and ECotality, Inc (The EV Project) are part of DOE grants that involve installation of charging stations. ECotality will deploy nearly 15,000 charging stations in 13 cities located in five states (Oregon, Washington, California, Arizona and Tennessee) and the District of Columbia [119]. Coulomb Technologies plans to install more than 4,600 charging stations in nine metropolitan regions across the United States by October 2011 [120].

Some other US charging companies include: Aker Wade AeroVironment, Plug Smart, Shorepower Technologies, and Clipper Creek. Infrastructure building activities extend beyond the USA to some international companies such as Eaton; RWE, E.ON, The Juice Bar, ABB, Elektromotive, Epyon. These are some other example of international projects:

- Denmark: The country is spending \$100M on EV infrastructure, including charging points and battery-swap stations and the goal is to run it with wind power [121].
- France: The French government has announced a ten-year, €2.5 billion program to jump-start vehicle electrification in the country. The money would be disbursed for incentives for the production and purchase of plug-in vehicles as well as upgrading infrastructure. The hope is to have one million charging points in place by mid-decade and four million by 2020 [122].
- Australia: Better Place Australia, the electric vehicle (EV) infrastructure and services provider, will roll out electric vehicle infrastructure city-wide in Canberra [123].

In addition, the C40 Cities group of large cities committed to addressing climate change has started the C40 Electric Vehicle Network which has committed to promote electric vehicle adoption in their cities. The C40 Electric Vehicle Network consists of: Bogotá, Buenos Aires, Chicago, Copenhagen, Delhi, Hong Kong, Houston, London, Los Angeles, Mexico City, Toronto, Sao Paulo, Seoul and Sydney along with automakers BYD Auto, Mitsubishi, Nissan, and Renault [124].

### 3) Standards

In order for a multiplicity of vehicles to interoperate between smart grid enabled sources of charging, a multiplicity of standards exists. This includes the physical connections though the communications to how to pay for the charge. Unification of plug standards and charging protocols will allow the EV industry to realize a common charging

infrastructure. This will reduce the system cost and accelerate adoption.

Standardization on the charging plug is a major key step and this was first realized in the early 1900's, with the early electric cars. Early EV adopters of the 1990's were used to bringing adaptor kits with them and the EV industry wants to move away from this experience

The SAE charge plug standard J1772 has gone through major revisions (for example the November 2001 revision used the AVCON connector) and the current revision adopted on January 14, 2010 [125] is on track to be widely adopted.

However, Level 3 charging is not yet incorporated into the standard and Europe has the IEC 62196 standard [126]. Level 3 is being incorporated into both J1772 and IEC 62196. In addition Japan's "CHAdeMO" (stands for Charge and Move) association has adapted a separate DC fast charging connector first developed by TEPCO for JARI. The CHAdeMO plug is the current de facto standard for Level 3. As a result of these different standards the Nissan Leaf will come with both the J1772 plug and the CHAdeMO plug (Fig. 8.). Finally, as indicated before, a revision of J1772 to incorporate DC fast charging is expected out August 2011 [106].



Fig. 8. Nissan Leaf fast charging JARI CHAdeMO plug (Left) and SAE J1772 Level 1/2 plug right. Used with permission from Datsun.org.

### 4) Public charging infrastructure cost

Public charging infrastructure and the issue of who pays is a more complicated issue. Government funded programs, such as recent awards from the U.S. Department of Energy, will pay for initial installations of charging infrastructure. However, it is unclear whether the private sector can demonstrate a viable business in installing such infrastructure and charging users for the privilege of charging. One perspective is that the price charged to users must be significantly higher than the cost of electricity, in order to recoup the investment cost, if the sole business is to "sell" the battery charging service. Of course, a significant premium over the cost of retail electricity would make the EV less cost-effective for the vehicle owner, thus eroding some of the value proposition.

Another concept is that retailers or mall operators might pay for EVSEs, to encourage greater foot traffic and longer stays within their stores. For example, a Level 2 charger might cost \$2000, but could result in additional sales to the retailer, in addition to providing the “halo effect” benefit of being a “green” or environmentally-conscious business. Similarly, in urban environments where drivers rent parking spaces, a parking garage owner might choose to install EVSEs and charge a premium to those customers who desire that capability.

One challenge in building the grid infrastructure to accommodate greater numbers of EVs and PHEVs is the utility business model. As a regulated monopoly, utilities must apply for rate recovery for investments made to benefit their customers. Regulators, such as the local public utilities commission, have significant discretion regarding what costs are applied to the rate base and passed on to customers. Thus, utilities need clear guidance that can lead to cost recovery for investments designed to promote greater EV penetration. Perhaps more problematic may be the tendency for some utilities to favor large, costly projects rather than programs to promote efficiency or greater utilization of existing assets. A utility gets a regulated rate of return on capital investments required on the system. Thus, there is little incentive to reduce peak energy use or to shift usage to overnight hours, as this would reduce the size or cost of projects, of which utilities earn a percentage. Moreover, utilities may not be able to apply the cost of chargers to the rate base and thus would have little incentive to create a network of chargers to help accelerate adoption of EVs. Some utilities have progressive regulators who recognize the value of increasing efficiency and thus reward programs that encourage efficiency and reduce demand. AMI or smart meters is one area where utilities have obtained regulator approval for investments in the system that can help greater EV adoption.

Automakers, utilities, infrastructure providers, and battery suppliers are working in concert on the development and deployment of grid-connected vehicles. In some cases, cities and local governments are playing a major role in establishing best practices to accommodate grid connected vehicles. Nissan, General Motors, Toyota, and other manufacturers have established relationships with utilities across the country to prepare for the next generation of grid connected vehicles. Such partnerships allow both the vehicle producer and the fuel supplier to develop both sides of the vehicle/grid equation in tandem. Such demonstration and deployment projects are critical to the success of the large scale consumer roll-out of these vehicles.

GM will provide 10-12 utilities with demonstration Volts for “practice:” tracking and managing the load, the charging experiences, the relationship with the charging equipment with utilities’ substations, transformer-type regions, etc.

Nissan is also a supporter of Level 3 DC fast charge, unlike most other automakers. Their strategy is to deploy infrastructure across six states with multiple DC fast-charging stations.

#### *D. Education*

Another challenge that must be addressed in order to accelerate adoption of EVs and PHEVs is consumer education.

Many separate efforts are underway to spread information about electric drive vehicles. Significant work, for example, has been done by the Electrification Coalition, which has published a roadmap for the electrification of transportation [96]. The Electrification Roadmap serves as a policy guide, laying out the arguments for electric drive vehicles, while identifying specific policies that could help accelerate the production of such vehicles and their integration into the electricity and transportation systems. There are many companies facilitating the charging infrastructure, and the EV Project [127] is one that raises public awareness. The Electric Drive Transportation Association (EDTA) is an industry organization representing vehicle and equipment manufacturers, energy providers, components suppliers and users [128]. EDTA has been instrumental in helping to move legislation that advances electric drive technology. To engage the public during Earth Week 2011, EDTA will have an EV parade/motorcade to the Nation’s Capital with stops at the Department of Energy, the White House, and Capitol Hill with the final destination a public Ride, Drive & Charge press conference. The National Plug-In Vehicle Initiative (NPVI) is a new organization, comprised of automakers, utilities, battery and component manufacturers, associations and government entities, that has the mission to provide timely and accurate information to policymakers, media, and consumers about the electric drive industry. Set America Free is an organization dedicated to educating people about the danger of dependence on foreign oil and the need for fuel choice, including the use of plug-in hybrids [129]. Organizations are using the internet to raise awareness, through such sites as ProjectGetReady.com [130].

There are many grass-roots organizations that are also working to spread information about EVs and PHEVs. CalCars, [131] Plug In America, [132] Plug-In Partners, [133] and the Electric Auto Association [134] are just a few in the U.S. Worldwide, organizations like the World Electric Vehicle Association [135] (WEVA) and the European Association for Battery, Hybrid, and Fuel Cell Electric Vehicles [136] (AVERE) promote the use of electric drive vehicles. These organizations help organize and support industry events, like the Electric Vehicle Symposium (EVS), which is one of the largest and longest-running forums for networking and sharing of technical information about electric drive vehicles.

The state of California was the first state to adopt a Zero Emissions policy for Electric vehicles, in 1990. Since then the Zero Emissions for Vehicles ZEV program [137] has undergone many changes. With a Technology Symposium and an Independent Expert Review Panel to update all ZEV technologies, they have held public meetings for all interested parties to promote the overall program and ZEV infrastructure issues.

Despite these efforts, however, the general public is largely uninformed about electric vehicles and their advantages. Public awareness is an important aspect of the whole system, since widespread adoption is impossible if people aren’t aware of the availability, use, and advantages of the vehicles. In order to reach the general public, the effort must be broadened from policy and enthusiast organizations, to include mainstream media, the internet, and high-profile events. Chris

Paine's 2006 documentary "Who Killed the Electric Car" explored the failed introduction of electric vehicles in the mid 1990's [138]. The film elevated the profile of electric vehicles, raising awareness and bringing attention to the entire industry. A sequel entitled "Revenge of the Electric Car" is reportedly in production.

Individual automakers have conducted campaigns to raise awareness about their particular products. GM, for example, used a viral marketing campaign around the number "230" to make the point that their Chevy Volt could achieve 230 miles per gallon (though the assumptions leading to this number are debatable). Nissan has also used new media, with a smart phone apps campaign around zero emissions to help spread the word about the Leaf EV.

Demonstration programs are being initiated at national, state, and city level. In August 2009, the U.S. Department of Energy awarded millions of dollars to various companies, universities, and organizations to institute programs designed to increase awareness of electric drive technology [50]. This funding was under the category, "Advanced Electric Drive Vehicle Education Program", which was a portion of the Recovery Act Awards for Transportation Electrification. Recipients of funding included programs for secondary, undergraduate and graduate students, emergency responders, and the general public.

The effort is not just in the United States. Around the world, entire cities are being designed from the ground up with energy use and the integration of new technologies, such as electric vehicles and the smart grid, playing a central role. These demonstration projects could indeed be models for future development.

China has announced plans for a renewable energy demonstration city in Turpan. Turpan, which is located in the Xinjiang Uigher Autonomous region, receives 3200 hours of sunshine a year, making it an ideal candidate for solar energy. The city plans to use electric buses and taxis, powered by this solar energy [139].

Abu Dhabi's ambitious Masdar Energy City project will be powered entirely by renewable energy [140], [141]. Sharable EVs will provide transportation. These and other new cities have the potential advantage of being designed with the entire system in mind, from the start. This allows the various components, like the solar panels, electric vehicles, and charging infrastructure, to be seamlessly integrated, optimizing the overall system. Although a fully-integrated, clean sheet approach may be ideal, most of the world will have to be retrofitted, reusing many existing components.

#### E. Potential threats to the grid

Although there is already ample generating capacity to accommodate EVs, especially if charging is done overnight, the *distribution* of electricity may be a problem at the neighborhood level. Adoption of EVs is expected to be relatively gradual, thus giving utilities time to upgrade their distribution systems, just as they did during the introduction of refrigerators, air conditioners, and modern flat-screen TVs. At the same time, though, experts expect that the distribution of EVs will be "lumpy," with early adopters clustered in certain neighborhoods, due to demographics such as income and

educational level. This may cause local strain on transformers and other infrastructure.

EPRI has conducted many studies on GEVs on distribution grids [142]- [147]. The EPRI study [147] illustrated the potential localized impact of PHEVs on the distribution system. This study picked a representative summer day and assumed 10% PHEV penetration, charging at 240 V, 12 A. If the charging started at 6:00 pm, the load to the substation increased as illustrated in the upper curve in Fig. 9. This would cause additional strain on the system, which could be a serious issue on a hot summer day. If the start of charging is staggered between 9:00 pm and 1:00 am, however, the additional load would have minimal impact to the distribution system, as shown in the lower curve of Fig. 9 [147].

A vehicle being charged at 15 A at 220 V draws 3.3 kilowatts of power, which is roughly equivalent to the average load that a home draws from the grid. Each charger increases home current requirements by 17-25%. Although this charging may be done overnight, if multiple vehicles are plugged on one circuit that is close to its limit, the additional load on the neighborhood transformer may cause it to fail. If utilities know where EVs and PHEVs are expected to be plugged in, they can perform the necessary upgrades. The challenge is predicting where these vehicles will be charged.

Although there are many mechanisms by which auto dealers, state motor vehicle departments, insurance companies, and utilities might be able to pinpoint the locations of such vehicles, privacy concerns and logistical hurdles have slowed the development of systems to identify the residential locations of these vehicles to allow utilities to plan upgrades.

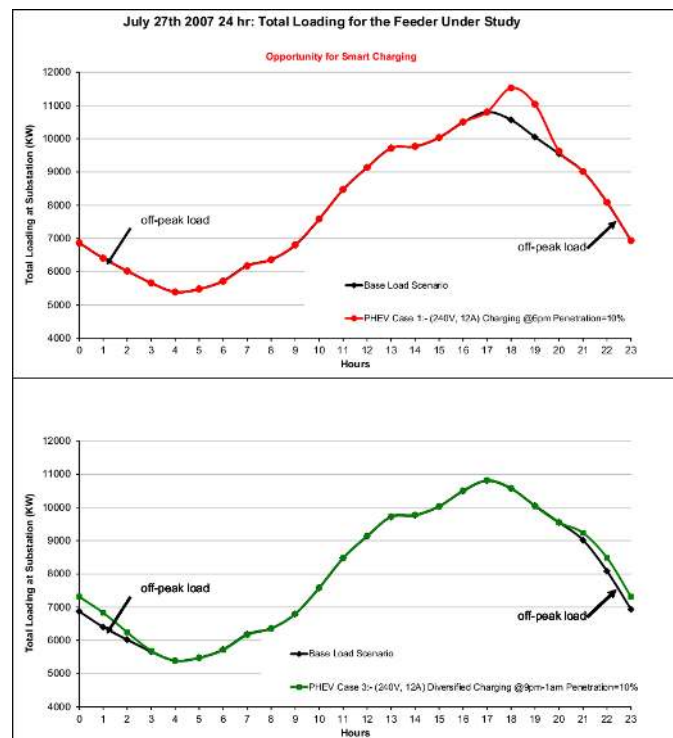


Fig. 9. Comparison of load during a summer afternoon. The top curve assumes 10% of vehicles are PHEVs which all start charging at 6pm. The bottom curve assumes 10% of vehicles are PHEVs, but the start of charging is staggered between 9pm and 1am. Used with permission from [147].

In the absence of coordinated systems to obtain this information, there may be other ways for utilities to identify the locations of EVs and PHEVs. The characteristic charging profile of a new EV owner should be relatively easy for a utility to recognize, for example by an increase in energy usage every weekday at 6:00 pm. In addition, utilities may develop relationships with EV owners during the charger installation process or through incentive programs to encourage certain behaviors.

Energy storage can also be used to buffer the impact of the vehicle on the grid. Some companies are pursuing strategies where energy is stored in a battery built into the EVSE hardware. The advantage of such an approach is that the EVSE battery can be charged overnight, at the lowest cost and impact to the grid. This energy then can be used to charge the vehicle at any time without increasing the load on the grid. This strategy also allows for faster charging, while minimizing the impact to the grid. The downside of this strategy, of course, is the additional cost of having a battery in the EVSE. The additional expense is more easily justified in a commercial environment where multiple vehicles are charged per day or where high-power charging is required due to the size or usage of the vehicle, or where there is a surplus of energy from a renewable energy source.

Although fast charging can help alleviate range anxiety, automakers, battery manufacturers, and utilities largely prefer slower, overnight charging, when there is plenty of baseload power [137]. Each has its own reasons, but they all relate to cost. Automakers are trying to reduce the cost of EVs. Thus anything that adds additional cost must offer commensurate benefits or value. For many automakers, faster charging beyond Level 2 is not perceived to have sufficient value to the end user to justify the additional expense in vehicle and charger hardware. Battery manufacturers (and automakers) want to ensure that the battery lasts the life of the vehicle. Since fast charging shortens the life of today's batteries, the downside outweighs the advantages of convenience to the consumer.

In summary, charging and grid infrastructure are manageable challenges. Although some warn that the sudden adoption of EVs and PHEVs could destabilize the grid, the opportunity that such vehicles present is greater than the threat they pose. Properly managed, through smart chargers, smart grid, smart policy, and energy storage, the potential strain on the grid can be minimized.

#### *F. Opportunities for the grid*

EVs and PHEVs represent a significant opportunity for the electric power industry. If grid-integrated vehicles quickly gain popularity, the growth in load could be significant. From the perspective of the overall grid efficiency, the most advantageous time to charge vehicles is off-peak or in the overnight hours, when there is excess generating capacity. By charging vehicles at these times, the overall load curve is flattened, thus increasing the utilization rates of existing power plants and assets. This maximizes the use of the existing baseload generation and other transmission and distribution assets.

It is possible to use market signals to encourage off-peak vehicle charging. Utilities can offer time-of-use or dynamic

pricing, in order to encourage EV owners to charge overnight when prices are lower. Chargers can be programmed to take advantage of this lower price. However, given the relatively small difference between peak and off-peak electricity pricing, compared to the large savings the owner achieves compared to gasoline, it remains to be seen whether this economic signal will be enough to discourage peak charging.

EVs create a significant new class of demand for electricity generated from renewable sources. Since their batteries can typically store 10-35 kWh, they can serve as a flexible load for intermittent energy sources. Wind farms generate power even when the demand is low. In the overnight hours, when baseload generation is sufficient to meet the load, there is little use for that wind-generated power. Vehicles being charged on the grid represent a large potential overnight load, which could take advantage of the excess wind power generated at that time. Photovoltaic solar energy has a better correlation between generation and load, as power is generated during the day when demand is high. Solar panels on rooftops or free-standing solar carports might be an excellent method of charging vehicles using a renewable resource, while minimizing the impact of daytime charging on the grid.

Although vehicle batteries connected to the grid are one possible method of mitigating the intermittency of distributed solar, home energy storage and community energy storage are other possibilities. BYD's development in Lancaster, CA is an example of a project to integrate rooftop solar with batteries. In this project, BYD is supplying the solar system and the home energy storage unit [148]. By working with the builder, BYD offers the customer a streamlined buying experience. In the future, similar strategies with vehicles and home chargers might help accelerate adoption.

Another example of using vehicle batteries to store renewable energy comes from Denmark, which is offering 227,000 kr (US\$40,000) in incentives for the purchase of an EV, plus a downtown parking spot. Denmark is spending over a 567 million kr (US\$100 million) on EV infrastructure, including charging points and battery-swap stations [121].

Battery Electric Vehicles (BEVs) can operate as renewable energy generators when connected to the grid (V2G), providing greater flexibility in the management of renewable electricity supply to residential and commercial consumers.

#### *G. Safety*

One possible issue is regarding the perceived safety of lithium ion batteries in vehicles. Concerns about safety are more about perception than reality, as automotive products must pass extremely stringent safety testing, far beyond those required for most consumer products. Iron phosphate and manganese oxide based chemistries currently being used in vehicle batteries are widely recognized as being safer than the cobalt-based oxide chemistries used in consumer lithium ion batteries. In addition, vehicle battery packs are engineered to protect the battery from physical, electrical, and thermal abuse. As a result of engineering design based on the failure modes and effects analysis (FMEA), abusive situations are not likely to exist in a battery pack during normal operating conditions. However, in the event of multiple failures in the battery's systems, battery packs are still designed to be safe. During catastrophic circumstances, such as a car accident,

most battery packs have sensors which will trigger a signal to open switches or contactors to immediately disconnect or de-energize the pack.

The US is getting prepared for the EV national roll out with comprehensive safety plans with National Fire Protection Association's (NFPA) emergency responder safety training program for advance electric drive vehicles. The program began in 2010 and goes through 2013 with the goal to implement a comprehensive Emergency Responder training program based on NFPA codes and standards. The plan is to reach 1.1 million fire service members, reduce fire fighter and civilian EV concerns, and offer courses to EMS and law enforcement and have the Emergency Responder Web Portal online in 2011 for all EV safety training and information. The program is funded from the DOE and contractors/partners with a total budget of around \$5.4 million dollars [149]. The Fire Protection Research Foundation, a research arm of the NFPA, has produced a report on fire fighter safety and emergency response for EVs and HEVs funded by the Department of Homeland Security [150].

Finally, the lack of noise from EVs and hybrids has been a safety concern with car manufactures addressing in different ways. The Pedestrian Safety Enhancement Act of 2010 passed by both the House and the Senate proposes a certain minimum amount of 'alert sound' from EVs and hybrids so that the blind or pedestrians can hear the vehicle when it's traveling at constant speed, accelerating or decelerating. It does entertain the possibility of a 'cross-over speed' at which a vehicle emits enough sound on its own. The bill does not specify the minimum levels or nature of the alert sound but provides funding for the secretary of Transportation, who would set the final rules [151].

#### IV. POLICIES

With the support from governments to transition the whole system, the transportation sector could rapidly embrace the opportunity for industry transformation with the electrification of the vehicle. Numerous policies for each area of the EV industry have begun to be adapted both nationally and internationally. Battery and vehicle cost are the biggest barriers to wider adoption rate. However, the true comparison is the total cost of ownership for EVs and PHEVs, and the payback period, compared to the conventional ICE alternative. Clearly, policies that lower initial cost of EVs and PHEVs will accelerate adoption. As mentioned previously, the current federal rebate for EVs and PHEVs in the U.S. ranges from \$2500 to \$7500, depending on the size of the battery. Increasing tax credits would provide additional incentive for consumers. Many States have offered cash incentives of up to \$5000 and each state has other varied approaches [56] to encourage consumers. Some are working to convert tax credits into instant rebates at the time of purchase. This would lower the initial out-of-pocket cost to the buyer, simplify the process by reducing paperwork, and also ensure that all buyers, regardless of tax liability, can benefit.

The U.S. government is also addressing the issue of cost by increasing the supply base for key components. The U.S. Department of Energy (DOE) awarded hundreds of millions of

dollars to manufacturers of batteries and electric drive components to help accelerate the production of critical components in EVs and PHEVs [50]. The DOE Advanced Technology Vehicle Manufacturing (ATVM) program has also provided conditional loan commitments to major automakers, including Ford, Nissan, Tesla, and Fisker, as well as one parts supplier, Tenneco [152]. Additional incentives, or the acceleration of disbursement of funds from existing programs, would help manufacturers in the electric drive industry lower the cost of vehicles and vehicle components.

Apart from strictly the financial costs, these programs also are critical in accelerating the development of the manufacturing supply base. Thus, shortening the time required to create the EV "ecosystem" is also an important goal of such programs. President Obama set the goal of one million PHEVs on the road by 2015. This ambitious target can only be achieved through concerted, sustained effort from the public and private sector.

Increased R&D funding can also help drive down the long-term costs of components and vehicles, while increasing their functionality. In addressing EV range, battery technology has been one key focus area of government-funded programs. The United States Advanced Battery Consortium (USABC) is the umbrella organization for collaborative research between Chrysler, Ford, and General Motors on electrochemical energy storage. Awardees of USABC funding include all of the major U.S battery manufacturers, in addition to some foreign companies that have significant U.S. operations. The heightened interest in developing better battery technology was reflected by additional funding and awards made in 2010 by USABC. In the area of long-range research, the Advanced Research Projects Agency – Energy (ARPA-E) has also awarded hundreds of millions of dollars to accelerate innovation in energy research [153]. Policies which increase the operational cost of conventional ICE vehicles, but do not increase the operational cost of EVs and PHEVs, would have a similar stimulative effect on the adoption of EVs and PHEVs, by shortening the payback period. The obvious, most straightforward approach would be to increase the gas tax. Many have advocated a gradual increase of the gas tax, phased in over several years to allow industry and consumers to adapt. However the political will does not currently exist to increase the use of this policy instrument in the U.S. Another alternative is a feed-in tariff or licensing/registration fee that provides a greater economic incentive to EVs and PHEVs. Such a program can be revenue-neutral. Greater awareness of electric drive vehicles and the use of carbon-free energy to power transportation could reduce resistance toward policies like a gas tax or feed-in tariff, in turn prompting action among the world's leaders. Consumers might be more inclined to support a higher gas tax if alternatives were available that lowered or eliminated their need to buy gas.

Regulations that set standards for vehicle emissions can also incentivize the use of electric drive vehicles. In April 2010, the Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) announced [154] a joint rule establishing a program to reduce GHG emission and improve fuel economy for new cars and trucks sold in the U.S. This program applies to vehicles in model years 2012 through 2016. Work has already begun on

developing rules for 2017 and beyond. The existence of electric drive vehicles and the infrastructure for wider adoption are critical in the future rulemaking process. The rules for 2017 and beyond will depend on whether electric drive vehicles are widely available and have been embraced by the public. In a self-fulfilling prophecy, the likelihood of such rules also encourages automakers to develop electric drive vehicles, which in turn makes it more likely to have regulations that favor these vehicles.

Bills to expand tax incentives and spur regional EV growth are being developed and restructured to support various aspects of the EV market such as the Electric Vehicle Deployment Act [155], [156].

The economic value of EVs and PHEVs can also be enhanced by monetizing the reduced lifetime emissions of such vehicles through carbon credits or cap-and-trade policies. Other possible policy instruments include the second phase of the Renewable Fuels Standard (RFSs) and Low Carbon Fuel Standard (LCFS). The method of calculating carbon intensity and life cycle emissions has been contentious, particularly from constituents supporting corn-based ethanol. Nonetheless, these policies provide a potential mechanism for incentivizing electric drive vehicles.

Policies that lower the cost of installing charging infrastructure would also help accelerate adoption. Currently, the Alternative Fuel Vehicle Refueling Property Credit allows a tax credit equal to 50% of the cost of electric vehicle charging equipment up to \$2000 for individuals and \$50,000 for businesses [157]. This credit was set to expire at the end of 2010. At the time this article was written, this tax credit had not been extended. Allowing charging infrastructure costs to be applied to the rate base would also encourage utilities to install such equipment. In addition to charging hardware, other infrastructure upgrades, including software and communications systems, should be eligible for tax credits. These investments in infrastructure are important to address consumers' concerns regarding EV range and convenience. In many ways, perception can be just as important as reality. If consumers perceive the chargers are plentiful, they will not have the same range anxiety, even if they always charge at home and never use public charging infrastructure.

The federal government could offer warranty insurance to help reduce the cost of EVs and PHEVs. In his book, "Freedom From Oil," David Sandalow proposed a government-sponsored warranty insurance program where the Original Equipment Manufacturer (OEMs), insurance companies, and the federal government share the risk [158]. This would reduce the cost of EVs and PHEVs by limiting the possible financial exposure to automakers and insurance companies. In this case, the federal government only provides the backstop; OEMs and insurance companies would assume the risk before the government.

Local, city, and state governments have begun to offer benefits to drivers of EVs to accelerate EV adoption. California, for example, extended the carpool-lane (HOV) access for EVs through 2015 [159].

Many possible incentives are available: incentive by rate, income tax or deduction; sales tax exemption; car pool access; infrastructure purchase or upgrade rebates or tax breaks; free parking; reduced congestion charges or tolls. At the time of

writing there are 12 states with incentives in addition to the federal incentives, and six states that offer infrastructure incentives [56].

Various stakeholders are involved in the process of developing and deploying electric drive vehicles. Automakers, components suppliers, charging infrastructure companies, utilities, governments, and the public all contribute to the overall success, but sometimes do not share the same perspective. Each is dependent on the other and the different, interrelated elements must be coordinated, in order to accelerate adoption. The challenge is to identify the points of common agreement, then to build upon that foundation to address the challenges that all face.

Other national governments have come together to take action towards a global transition via The Clean Energy Ministerial [160]. Global initiatives most relevant to this paper include: The Electric Vehicles Initiative (EVI) [41], The International Smart Grid Action Network (ISGAN) [161], and the Multilateral Solar and Wind Working Group [160]. Participating governments account for about 80% of global energy consumption, and include Australia, Belgium, Brazil, Canada, China, Denmark, the European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Norway, Russia, South Africa, Spain, Sweden, the United Arab Emirates, the United Kingdom, and the United States.

The public also plays a critical role in advancing electric drive vehicles. If the public were to convince its leaders to make binding commitments to reduce CO<sub>2</sub> emissions, there would be tremendous pressure to accelerate the adoption of EVs and PHEVs, as expanded use of electric drive vehicles offer one of the most effective ways to reduce consumption of fossil fuels. Average consumers, however, must be made aware of the current advantages of these vehicles before they will feel compelled to take action.

A global treaty with funds, technology transfers, and a structure to commoditize and regulate GHGs could further spur development of the EV industry and support national programs, around the world. Instituting global enforceable energy and clean environmental policies (e.g. The Kyoto Protocol [19] and The Copenhagen Accord [22] and the Cancun Agreements [23]), could also have a large effect on the rate of EV adoption.

## V. CONCLUSION

Electric drive vehicles are one of the best ways to reduce our use of petroleum-based fuel and better regulate GHGs. With the electrification of transportation and utilizing the emergent smart grid, there is the opportunity to intelligently integrate our transportation and energy systems: this may provide the foundation for wiser choices for ourselves and our world.

Governments and private industry recognize the critical role that electric drive vehicles will play in the future of transportation. It will require collaboration of not only industry sectors but also of citizens, consumers and governments to accelerate change. The question now becomes how quickly the transition will occur [158]. In order to make

this transition as seamless as possible, these efforts must be coordinated to ensure that the benefits are maximized while minimizing the cost. With the support from governments to transition the whole system, the transportation sector could rapidly embrace the opportunity for industry transformation with the vehicle electrification. All of the following are key to such transformation: policies that jump-start industry sectors through incentives related to all the components that make up this whole system; electric vehicle manufacturing; advanced battery research; best practices for extraction and mining of rare earths and lithium; development and deployment of EV technologies; standardization of industry protocols of plugs and chargers; public education; and national and global political will for the adoption of smart grid technology and renewable energy sources.

#### ACKNOWLEDGMENT

The authors would like to acknowledge Yini Qiu of World Team Now, Brigid Crumlish of CCLS, and Debra Abbott for their help in preparing this paper.

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She is the Founder and President of the social and environmental non-profit, World Team Now, the CEO of World Team- Building, LLC, and the leader of the emergent World Team multi-media project. She has produced many global "outside of the box" projects since her first multi-media production, which was part of the Asia Pacific Expo, in Japan 1989. Suzanne's global policy journey began in 1992 when she worked for USA Presidential Candidate Jerry Brown. From there, she was involved with the United Nation's Earth Summit/Global Forum in Rio and has continued to participate in the UN conferences around the world. Her latest role was as a journalist for Environment News Service World-Wire with COP15 and covered the E-Race. At EVS21 in Monaco Suzanne was part of the EV parade and rode in Corège's concept vehicle, while there to produce the Alternative Vehicle parade as part of the Monaco Grand Prix. As a journalist, she wrote about film, sports and travel for a local Malibu paper, and as a public speaker she has addressed many international audiences. The World Team development journey has included collaborations and support from academic organizations such as Columbia University's Computational Learning Systems, CCLS; Pepperdine University's Graduate School of Public Policy, and the International University of Monaco's Business School. Her Bachelor of Arts degree from Sarah Lawrence College

gave her the framework to acquire knowledge and inspired her global travels that wove an adventure for an experiential education.



**David L. Waltz** is Director of the Center for Computational Learning Systems at Columbia University. He received all his degrees from MIT, including a Ph.D. in 1972. Before coming to Columbia in 2003, Dr. Waltz spent 10 years at NEC Research Institute, where he was President from 2000-2002. From 1984-93 he directed data mining and text retrieval R&D at Thinking Machines Corporation and was at the same time Professor of Computer Science at Brandeis University. From 1973-84 he was on the EE faculty at the University of Illinois at Urbana-Champaign. He is a Senior Member of IEEE, Past President of AAAI (American Association for Artificial Intelligence), a Fellow of ACM (the Association for Computing Machinery), and a Fellow of AAAI. He was a Board member of CRA (Computing Research Association), and former Chairman of ACM SIGART (Special Interest Group on Artificial Intelligence). His thesis on computer vision originated the field of constraint propagation and, with Craig Stanfill, he originated the field of memory-based reasoning. His research interests have also included machine learning and applications, especially to the smart grid, information retrieval, data mining, protein structure prediction, and natural language processing.