Steering the Electric Vehicle Transition to Sustainability

July 2018

A White Paper from the National Center for Sustainable Transportation, the Plug-in Hybrid & Electric Vehicle Research Center, and the Sustainable Transportation Energy Pathways Program at UC Davis

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National Center for Sustainable Transportation

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PLUG-IN HYBRID & ELECTRIC VEHICLE RESEARCH CENTER
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of the Institute of Transportation Studies

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STEPS White Paper Process

The Sustainable Transportation Energy Pathways (STEPS) Program prepares white papers that synthesize research insights from various projects to help address complex sustainable transportation transition issues and inform the discussion for decision makers in industry, government, and civil society. Following a public release, the research team seeks to publish this paper in a peer-reviewed journal.

U.S. Department of Transportation (USDOT) Disclaimer

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Prologue

I was lucky in my college years to join a team of ocean rowers and cross California's Monterey Bay in a Whitehall, a sleek wooden row boat favored by liquor smugglers in the 1920s. Four of us sat on wooden benches, our backs to the Monterey shore, our destination, each with both hands on a single fourteen-foot oar. Lee, an old fisherman friend, sat at the back of the boat, looking at and over us. Using only a compass, Lee steered, yelling "harder on starboard" or "harder on port" as we plunged into 20 miles of thick fog, a hazard of California summers. When all four of us pulled hard, synchronously, the big Whitehall would surge out of the water. It was exhilarating and with lunch in mind and Lee's calls to action, we pulled for hours, sliding in the hushed fog past thousands of giant jellies until we popped out of the fog two hundred feet left of Lee's target, the old fisherman now grinning in the bright sun. I take inspiration from that experience, about coordinated efforts and reaching goals, even when the immediate territory is shrouded.

Getting to Zero; Steering a Transition to Plug-in Electric Vehicles

The zero-emission vehicle (ZEV) endeavor has come a long way since the early 1990s and increasing numbers of transport energy experts are hopeful that electrification of vehicles, together with greening of the grid, provide a two-punch solution to reduce urban air pollution and meet radical carbon reduction goals. Technical progress of plug-in electric vehicles (PEVs) has been impressive; in particular, lithium ion batteries are more reliable, their energy density has improved, and their prices have fallen, faster than many experts expected. Engineers have three or four generations of vehicle designs under their belts, and electric vehicle profitability might be coming into view.

There are now more than 3 million PEVs registered around the world, and since 2010 the global PEV market has been growing at a rate of at least 40% per year, with the rate of growth for 2018 looking like 70%. With over 1.2 million sales in 2017, PEVs have reached 1.2% of annual global automotive sales, often concentrated in "beachhead" regions like Norway, California, China and Sweden, all with comprehensive policy programs (Lutsey 2017; International Energy Agency 2017). Norway has demonstrated that generous discounts – the largest being a 25% VAT tax reduction- as well as a wide set of privileges for PEV drivers such as free charging and parking can spur sales; Norway's markets are reaching 50% of sales for PEVs, far ahead of even California, which has a web of incentives and regulations to push the market, just not as generous.

The challenge now is to completely displace a world industry and consumer demand for combustion engines in a time frame dictated by climate issues. This is a challenge that will have to be met with decades of effort from industry and governments.

Fortunately, like the technology, maybe the conditions for securing a global transformational process are ripening. Leaders in at least seven nations—including France, United Kingdom and

India—have recently announced intentions to phase out fossil fuel cars. China, the world's largest auto market is developing a set of regulations to sunset sales of fossil fueled vehicles by 2040. In Paris on October 23, 2017 the Mayors of London, Los Angeles, Paris, Mexico City, Seattle, Copenhagen, Barcelona, Vancouver, Milan, Quito, Cape Town, and Auckland all pledged to "progressively abandon combustion engines" from large parts of their cities by 2030.[1] In January 2018 California Governor Jerry Brown signed an executive order to put 5 million ZEVs on California roads by 2030. And joining the chorus are a number of automakers, most recently Volkswagen and Volvo, which announced in 2017 their intentions to phase out in coming decades production of vehicles that run solely on internal combustion engines (ICE), joining PEV leaders like BMW, BYD, GM and Nissan. To date, automotive companies have announced a total investment of $90 billion to be made in electrified vehicles, including PEVs and hybrid electric vehicles (HEVs) in next few years.[2]

In light of this initial technical and political progress, it will be tempting for policy makers in beachhead markets to pull in their oars thinking their job is done and leave it to the carmakers and power companies to row the rest of the way. But precisely at this moment of profitability, carmakers will have to convince increasing numbers of less adventurous buyers to make a big switch to electric. These buyers thus far have been less interested in and informed about the new technology. They may have less resources and less willing to take a risk. They may have desires for larger vehicles or attachments to tradition. Just when one aspect of the market, profit, is possible, all the stakeholders will need to pull harder on the oars to get to the destination in time.

Five Successful Strategies: A Policy System Foundation

Policy must at the right moment signal the future to buyers. This means not only helping to make PEVs a financially advantageous choice for buyers and profitable for makers and sellers, but also to signal to buyers and sellers that the auto industry is transforming now, that the future is clean and electric. Policy must become a system that leaves no doubt as to the direction and pace of change. And PEV policy systems must be spread from beachhead markets to the rest of the world. Luckily many experiments conducted in beachhead markets have produced valuable learnings. Here are five strategies that have worked so far.

1. **Vehicle purchase incentives** offset the higher purchase price of PEVs and encourage more buyers each year to try this new technology. Purchase incentives can take the form of tax credits, sales rebates, sales tax reductions, and feebates (a revenue neutral and dynamic system of fees on high emissions vehicles and a rebate on low emissions vehicles).
2. **Reoccurring incentives** can take many forms, including reduced or eliminated fees for parking, road, ferry and bridge tolls, annual registration taxes and electricity prices; free or

[1] http://www.chicagotribune.com/business/ct-mayors-emissions-free-cities-20171023-story.html
[2] http://www.autonews.com/article/20180115/OEM05/180119788/global-carmakers-to-invest-at-least-90-billion-in-electric-vehicles

reduced cost charging; as well as road system privileges in limited-access areas such as downtowns, and in high-occupancy vehicle and bus lanes. Called reoccurring incentives, these daily perks make PEVs attractive, make PEV buyers come back for second purchases, and in some cases do not require direct allocation of public funds (Hardman 2017) .

3. **Robust rollout of charging networks** will be needed to meet rapid PEV market growth (Hardman, Tal, et al. 2017). Charging networks must expand rapidly if they are to support a goal of 30-40% PEV market growth. For example, in California or France thousands of new stations per year will be needed in 2020, but in 2030 the need is far greater, for hundreds of thousands of new stations per year. Not until 2040, when PEV market growth tapers, will the need for charging networks also stabilize. Government intervention will likely be needed to motivate charging station installation, maintenance and attractive pricing.
4. **Widespread consumer understanding of and experience with PEV**s is critical. Consumers will need to be convinced to try a new technology they have not used. Political leaders must signal that the end of fossil fuel use in vehicles is approaching. Governments will need to include electrification in education systems and commit to public education efforts.
5. **Regulations imposed on automakers** create certainty so that they make investments with less risk. Such regulations include continued tightening of greenhouse gas (GHG) emissions and fuel economy standards and the ZEV program in California and its offspring in Europe and China. These policy systems must be durable, with strategies that last to at least the end of the next decade and maybe beyond, strategies that will adjust to the improving technology, massive growth, and increasingly tougher market segments that need to be penetrated.

Autos are not cell phones

There are complexities of the auto industry and its market that require the attention of long-term policy systems. The success of some technologies like smart phones suggest that technology can transform industries, like communications in a few years. Turnover of the automotive fleet is more like that of homes or refrigerators than of cell phones; many vehicles stay on the road for up to 20 years. Used vehicles account for more than two-thirds of sales per year in mature markets like the United States,[3] a percentage that is growing with vehicle reliability. When compared to the IT sector, automotive profit margins are lower and capital costs are higher. A cell phone sale can generate 50% profit, whereas a midsize car sale generally produces less than 10% profit, except in some luxury models.

Another serious challenge is rolling out the hundreds of vehicle styles and designs. PEVs are not yet available in many desired and profitable vehicle styles, in particular power-hungry crossovers, SUVs and pick-ups that are increasingly popular with buyers since gasoline prices

[3] https://static.ed.edmunds-media.com/unversioned/img/car-news/data-center/2017/nov/used-car-report-q3.pdf Edmunds reports 9.3 million used vehicle transactions in Q3 2017 for the U.S., which compares to 4.5 million new car sales in the same period.

are low. This challenge is multiplied by the many varieties of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Moreover, PEVs are not projected to be profitable until next decade. Gasoline and diesel remain abundant and cheap. The increasing fuel economy of ICEs and displacement of fossil fuels by PEVs could enhance the glut that keeps oil prices low. Although electricity is abundant and relatively inexpensive, the electric power industry faces its own challenges in switching to renewable energy. Furthermore, the companies that provide charging are not yet profitable.

In short, cars are not like smart phones. Like the four rowers in the Whitehall pulling hard together for hours, adjusting and staying "on compass," all PEV stakeholders must work together for many years. And the PEV market must surge, not coast to reach carbon reduction goals.

It's all about the batteries; Getting PEVs to cost parity and beyond

Changing the automotive industry will take decades of political resolve, and batteries and their peculiarities are at the center of this transformation. Lithium batteries to power vehicles face great demands; they must last for 15–20 years, recharge quickly, be safe in accidents, provide power for rapid acceleration, and store enough energy to propel a vehicle for hundreds of miles of driving before recharging, in the case of a BEV, or a practical distance in the case of a PHEV (for example a normal day of driving). Batteries must also cool and heat cars in tropics, deserts and snow storms. A familiar opinion among skeptics of batteries is that lithium ion batteries, while better than previous technologies such as lead acid or nickel metal hydride, still fall short of providing a substitute for gasoline or diesel, because they don't have the energy density of fossil fuels and take too long to charge compared to refilling a tank with liquid fuels. A more optimistic position is that a next generation battery technology, for example lithium air, that will double or triple the energy capacity of lithium ion, will be needed for PEVs to succeed. However, the optimists are feeling the wind at their backs right now, batteries are becoming a huge success. Increasingly, vehicle manufacturers, analysts and stakeholders across the battery and vehicle industry are optimistic about lithium-based batteries, which are greatly improved in the last two decades and promise further improvements to be made in the next decade.

As noted above, PEV stakeholders and policy makers are guided by a belief that PEVs, expensive today and made in small numbers, will become cheaper as volumes increase leading to a day when the cost to produce a PEV is roughly equal to a similar combustion vehicle (HEVs included). This moment is called cost parity. The costs of lithium ion batteries have been falling, even faster than many predictions. At the same time their energy density and durability have increased (Nilsson & Nykvist 2015). Still, the battery remains the most uncertain and by far the most significant challenge to cost parity.

Vehicle battery systems are expensive because they are complex; a complete battery pack is made up of many cells and other costly components that require many manufacturing steps. Cell sizes and shapes vary from thumb-sized tubular cells familiar in flashlights to flat "pouch" cells like those in a cell phone (but typically larger, about the size of a textbook). Peeling back the lid of a battery pack can reveal hundreds, even thousands of individual battery cells lined up side-by-side or stacked like books, divided into in several sub-units called modules. Vehicle "packs" also incorporate cooling systems and battery management software systems (BMS) for controlling charging and monitoring cell condition. Because each vehicle needs hundreds or thousands of cells, the price of these cells must be much lower than those in a cell phone battery and is usually negotiated by OEMs through multi-year contracts for millions of cells. If PEVs make it in the market, future battery companies will dwarf the scale of the present battery industry.

Calculating when the industry will reach cost parity depends on the type of vehicle being considered (BEV or PHEV), an expanding continuum of technologies, and a huge range of battery sizes. The size of battery packs in electric drive vehicles, including conventional HEVs and even fuel cell electric vehicles (FCEVs) varies greatly. Packs in hybrids are about the size of a 1 square foot ice chest. Packs in plug-in hybrids are about the size of larger ice chests, and the much bigger packs in BEVs are about the size of several ice chests joined together, spread beneath the floor of the passenger compartment of the car.

The energy storage capacity of each vehicle pack is normally measured in kilowatt hours (kWh) of electric energy capacity. One kWh typically powers a vehicle 3-5 miles depending on the size and weight of the vehicle, acceleration needs and other variables like aerodynamics as well as if the vehicle is being used on a cold day in Boston or hot day in Phoenix. The kWh of the pack will shape the electric range of the PEV between charging.

BEVs have the biggest batteries. They use only electric motors to power the wheels, and store energy in batteries to power the motors. Many of today's small BEVs have 30–60 kWh batteries, which will take a compact car 80-120 miles. The Tesla Model S performance luxury sedan boasts a large 60–100 kWh battery pack with thousands of cylindrical cells underneath the car (many ice chests) and correspondingly large range (250-350 miles). PHEVs, which combine a combustion engine and fuel with batteries and electric motors, have smaller batteries, around 7–20 kWh (size of an ice chest) that can propel the vehicle 10-40 miles on electricity; the hybrid combustion system will drive the car until it runs out of liquid fuel.

Auto and battery makers must cut costs in every way to reach an often-noted cost goal for battery packs of less than $100/kWh, including all components, that many think is the threshold to approach cost parity. Several of the newest BEVs have packs with about 60 kWh, which translates to $6,000 if cost goals are met, a hefty percentage of the price of a median priced vehicle, $35,000, in today's market.

So far, the mix of BEVs and PHEVs on the road varies greatly by market, depending mostly on policy. Globally, the split was about 60% BEVs and 30% PHEVs in 2017. Austria, China and Norway have more BEVs while Netherlands, U.K., and Sweden have had more PHEVs (at least initially). The countries with a BEV focus typically have policies in place that favor BEVs and tend to skip complex PHEVs, while the countries with a PHEV emphasis have tended to offer automakers and consumers a middle road. The thinking in PHEV-oriented countries is that PHEVs will appeal to a broader range of less adventurous customers and give them experience with PEVs sooner, therefore creating larger initial markets that will grow the battery market.

Research at UC Davis and elsewhere has shown that PHEVs with small batteries could produce limited emissions reduction benefit (Tal et al. 2014; Nicholas et al. 2016; Plötz & Funke 2017; Bjornsson & Karlsson 2015). However, in multi-vehicle households that have ICEs and PEVs, larger battery PHEVs can achieve similar carbon reductions to BEVs in the same household (Nicholas et al. 2016). Additionally, a market with many types of PEV drivetrains might grow faster than a market with only BEVs by providing a wider variety of options to consumers, depending on consumers' vehicle design wants, travel needs, and local infrastructure rollout.

Additionally, the different ways analysts calculate and compare vehicle production costs, purchase prices and annual or lifetime cost of ownership, varies greatly between BEVs and various types of PHEVs, and reflects those analysts' optimism and skepticism about progress on costs, in particular batteries. Some analysts have been including incentives in their estimates of price parity, even though most incentives in place today are slated to sunset in the next few years. A notable exception is the California ZEV program, which is not an incentive program but a requirement on major automakers to produce ZEVs; it serves as a policy "stick" that penalizes carmakers that fail to produce ZEVs. As such it serves as a market push for ZEVs that may play a role in price parity.

Additionally, a few academics and PEV supporters have been comparing costs of ICEs, HEVs and PEVs on the basis of what's called total cost of ownership (usually referred to as TCO). TCO is the purchase price plus all costs incurred during the period a vehicle is owned. This would include things like the cost of electricity or gasoline as well as maintenance. While TCO is a useful and rational way to compare costs, and some studies show that PEVs deliver savings over their life, there is little research to support the idea that consumers make decisions in this hyper-rational way. In fact, research by Turrentine and Kurani suggests that few consumers (if any) are this rational. As one car buyer in a recent study noted, he does such calculations every day at work, but not when buying a car. For this reason, this author contends predictions of cost parity are more sound when based on data associated with production and battery costs, than on studies which are based in TCO and incentives.

We don't not yet know what is the optimal set of BEV and PHEV designs that will both reach carbon and emissions goals and meet consumer desires. Nor do we know what mix of PEVs will expand the market fastest, especially given the demands on infrastructure that results from different mixes of PEVs—and their resultant battery designs—in any region. One trend is clear: as battery prices drop, batteries in both BEVs and PHEVs are likely to get bigger, thus altering the design of vehicles (bigger PEVs), power (speed) of charging equipment, and the geography of charging systems (bigger batteries require less infrastructure close to home), and ultimately the price of vehicles and their operation.

Policy must be adaptive to these shifting battery capabilities. Much of PEV policy so far has been aimed at expanding the market to achieve volumes, and progress is notable. However, there is nothing automatic about this process, and reaching a point of hoped for "market take off" is probably dependent on broad systems of policy that aim beyond that point. Keep rowing.

Creating Consumer Awareness, Knowledge and Experience with PEVs to Meet Climate Goals

While a majority of policies so far have attempted to attract buyers by offsetting high purchase prices resulting from high materials and production costs, more attention needs to be paid to consumer awareness, knowledge and experience (Kurani et al. 2016; Krause et al. 2013; Vergis & Chen 2015). This is a broad area that includes retail sales online, dealers, electricity sales, as well as public education at the community level. Policy makers have been reluctant to take this on because it can look like propaganda to those who oppose government action. But without a strong public education effort and support for changing the generally slow retail sales situation for PEVs, the market will not move fast enough to meet climate goals. Ultimately, the accelerated growth of the PEV market depends on purposeful development of consumer awareness, consumer willingness to take a risk, and increased availability of the types of vehicles consumers want.

At this early phase in the market, most PEVs buyers have been "pioneers," (also called innovators) motivated by the new technology, and their belief in its importance and dominance in the future. These buyers usually have greater resources, including knowledge, income and other resources that allow risk taking (i.e. they own multiple vehicles), as well as a place to put a charger at their home or office. And still, only a few of these pioneers have experience with more than one of these first designs—for example have owned and used both a PHEV with 40 miles of all-electric range (PHEV 40) and a BEV with 100 miles of range (BEV 100)—in order to make an educated choice between them. But these early buyers are the vanguard, and their experience will shape the market in their region. Education efforts must amplify their experiences the rest of the risk adverse market.

The majority of remaining buyers are not aware, knowledgeable nor have useful experience with BEVs and PHEVs. Some are even resistant to change. A large number of the majority buy vehicles in product categories like SUVs, vans and pickups for which there are few, if any, models available in the early market. Furthermore between 65–75% of Americans buy used vehicles only or buy new vehicles rarely. Dr. Ken Kurani of UC Davis, who has been studying the U.S. PEV market for over 20 years, found in his 2016 and 2017 surveys that only about 50% of Californian or American car buyers can demonstrate basic awareness of PEVs – and California's PEV sales rate (5%) is nearly four times the national sales rate (1.4%) (Kurani et al. 2016). A much greater number of California buyers lack basic knowledge about PEV brands, models, performance, costs, charging, environmental benefits or incentives. Fewer still have any experience with driving or charging a PEV.

A related challenge is the structure of retail automotive sales. Often-forgotten partners in the transition, many auto dealers are independent businessmen, who must take risks in stocking and selling PEVs. Retailers can serve as important educators as well, providing consumers with test drives and passing on their knowledge of the vehicles. Policies must synchronize with dealers to transform practices in this sector.

A complexity that PEVs face is that the light-duty vehicle market is heavily segmented, divided by brand, size, design (pickups, sedans) luxury vs. economy, seating capacity, power and functionality (all-wheel drive, cargo space). Depending on how one defines a distinct vehicle—some are merely rebadged—there are often between 200 and 600 discrete vehicle types in a mature market like California. In the early market, a few models have dominated, often with 80% of sales attributed to four or five PEV models out of 20–40 available. In California and nationwide, PEV choices (Tesla excepting) have been mostly limited to subcompact and compact vehicles, despite the fact that since 2012, with low gasoline and finance costs, many buyers have been shifting away from sedans to crossovers and compact SUVs. Dr. Gil Tal of UC Davis estimated that in 2014, these types of PEVs, (compacts, etc.) comprise only 12% of the U.S. market. Additionally, only those regions with good incentives have 20–40 models; regions with few incentives may have only a few makes and models available to test drive.

PEV sales expansion in this early market stage is most often achieved by adding a new PEV brand (for example a PEV Toyota) or style selection (a PEV pickup truck) or new technology (a bigger battery). Likewise, shrinking sales can often be attributed to reduced selection, as was the case in the U.S. in 2015, when supplies of the leading PEV models—the Plug-in Prius, Chevy Volt and Nissan Leaf—all drew down as manufacturers prepared to offer their second-generation designs in 2017. The selection of PEVs has grown in Europe and China and so has the share of sales.

Sustained market growth of PEVs depends on continued product rollout into popular vehicle segments, in particular those segments which are growing and profitable. In today's U.S. market realities of low gasoline prices and especially low fuel taxes, compact SUVs and crossovers are the fastest-growing market segments and are popular among higher-income buyers. The U.S. market share of midsized sedans has shrunk several percentage points since 2014, while crossovers grew 14%. Notably, crossover or compact SUV-style PHEVs are successful in Europe and Asia but few of these are yet available in the United States.

Stakeholders in these beachheads will have to augment manufacturer and dealer advertising with education efforts, including public "ride and drives" and mimic social marketing campaigns in public health. These efforts take considerable resources, even in affluent California. For perspective, automakers and dealers spend billions of dollars each year to advertise conventional vehicles in order to compete with each other. Educating the uninformed and inexperienced public about a new technology is a tall order by comparison. And until real profits are being made, is hard for automakers to adequately budget. In the next decade, stakeholders who want to prepare this market for continued growth will have to be ingenious and steadfast, leveraging institutions like the education system and getting auto retailers engaged.

Spreading the Word from Beachheads to Backwaters

So far, PEV buyers are concentrated in “beachhead” markets (Moore 2002; Hardman et al. 2016; International Energy Agency 2017) with market penetration of several percentage points in leading cities. On a percentage basis, Scandinavian nations have been successful as a group. Norway is a big standout for a small market (5 million persons and around 150,000 new cars per year), with PEVs accounting for over 31% of annual sales in 2017 and looks even higher in 2018. Although a tiny market, Iceland recently reached double-digit sales growth of PEVs. Sweden and Netherlands have markets around 5%. The U.K., France and Germany achieved PEV sales of around 2% in 2017. The U.S. PEV market grew rapidly in 2017, achieving 1.4%. However, the most significant in absolute numbers is China, nearing 2% of what is the world’s largest auto market with plans to hit 20% sales by 2025.

These beachheads have supportive, motivated national and/or local governments that offer broad regulatory and incentive programs to buyers. In most of these beachheads, the tax and sales incentives have often totaled—even exceeded—$10,000 for BEVs, with lesser amounts for PHEVs. Norway stands out for big tax benefits and excellent in-use (reoccurring) benefits, such as free charging, parking, bridge and ferry tolls (Mersky et al. 2016; Fearnley et al. 2015; Figenbaum 2016; Figenbaum & Kolbenstvedt 2016). Germany, which avoided incentives in the early years, embraced them in 2016. As a result, its previously lagging PEV market has now caught up and even surpassed the U.S. in 2017 with nearly 2% of sales. These governments have made public policy declarations such as national fleet targets. Some also have created regulations to back up the incentives. And in these jurisdictions, manufacturers have made available a variety of PEVs. California, Norway, Netherlands, and China have offered sizable tax benefits, charging discounts, parking and road system privileges including things like access to special lanes, free bridge tolls, preferred parking, and charging at workplaces. California’s ZEV program is being emulated in China and considered in Europe. Many of these markets have strong local support as well, with local building codes requiring prewiring for chargers (Mark van Kerkhof 2014). Additionally, beachhead markets have shown commitment to developing a public infrastructure for charging.

Outside these beachhead markets, which have up to 30 years of efforts behind them, significant challenges remain. The transition will not be automatic. Buyers in new markets must be educated. Policies and incentives must push and pull the market until the whole vehicle sector is transitioned and sustained. Infrastructure will take years to develop in backwater markets, and given the rapid technical changes and low profits in the infrastructure realm, will need to be pushed to stay ahead of demand.

Regulatory Systems and Policy to Transform an Industry

The market beachheads, such as U.S./California, Norway, Netherlands or China have comprehensive programs to encourage makers to make the vehicles and buyers to try the new vehicles (Hardman 2017; Wang et al. 2017). These programs include:

- Regulations such as California's ZEV program, European carbon laws;
- Purchase incentives including tax holidays or incentives or rebates;
- Reoccurring incentives such as free charging, special electricity rates, and special road use privileges like access to bus and high occupant vehicle (HOV) lanes and discounts on parking or access to central city zones like London.

These measures have been offered during the first years of the PEV rollout to make these new technologies less risky to car makers and more attractive and affordable for buyers. In California, the ZEV rule is in place until 2025, and throughout the world, tax and sales incentives are set to sunset in the next couple of years. Norway, China and the Netherlands give financial incentives in excess of $10,000. In the U.S., a federal tax credit of up to $7,500 has been rolled into two- and three-year PEV leases, which together with rebates in a few states offer consumers extremely affordable vehicle options.

For a variety of reasons, these incentives are limited in supply and duration; a few may not persist into the third phase of the market. For example, the U.S. tax credits are capped by number (200,000 vehicles sold per manufacturer), and incentives in Norway are limited by time. In the case of bus and HOV lane access, PEVs will use up spare capacity in those lanes in the next few years. Will these incentives run dry before batteries reach "cost parity" and the market is self-sufficient?

Notably, in all the beachhead markets, private buyers not government, are responsible for the vast majority of purchases thus far. This pattern is strong in California and Norway, where over 95% of sales are by private households. In some European markets, notably Netherlands, Sweden, U.K. and Germany, a high proportion of "private" car sales are actually "company" car sales that are essentially benefits; many white-collar jobs are remunerated with a car bought for them by their company. They are also a primary target of vehicle tax policy. A high proportion of PEV sales in these countries have been generated by tax breaks for PEV company cars. In general, commercial and government fleets are relatively small compared to private markets (in the U.S. about 20% of annual sales are commercial, and most of those are rental fleets). So far, these commercial fleets have not generated many sales; often because they cannot get the same incentives and have more complicated decision structures which make them less adventurous than individuals.

Perhaps the most-costly and yet arguably central policy is the offering of financial incentives to PEV buyers. The U.S. federal government offers tax credits of $2,500–$7,500 (depending on battery size). According to Dr. Gil Tal of UC Davis, as many as 50% of Nissan Leaf drivers interviewed said they needed the $7,500 federal tax credit to make their purchase (Hardman & Tal 2016; Tal & Nicholas 2016). A number of states give additional tax credits or rebates worth up to $5,000). California gives rebates up to $2,500. Up to 70% of PEV buyers in California have claimed these rebates. The primary problem with rebates is sustaining them year after year, especially as the market grows. Usually, such incentives will become smaller per vehicle commensurate with market growth. But ending such rebates prematurely can crash the market. After Georgia ended its subsidy in 2015, PEV sales there plummeted.

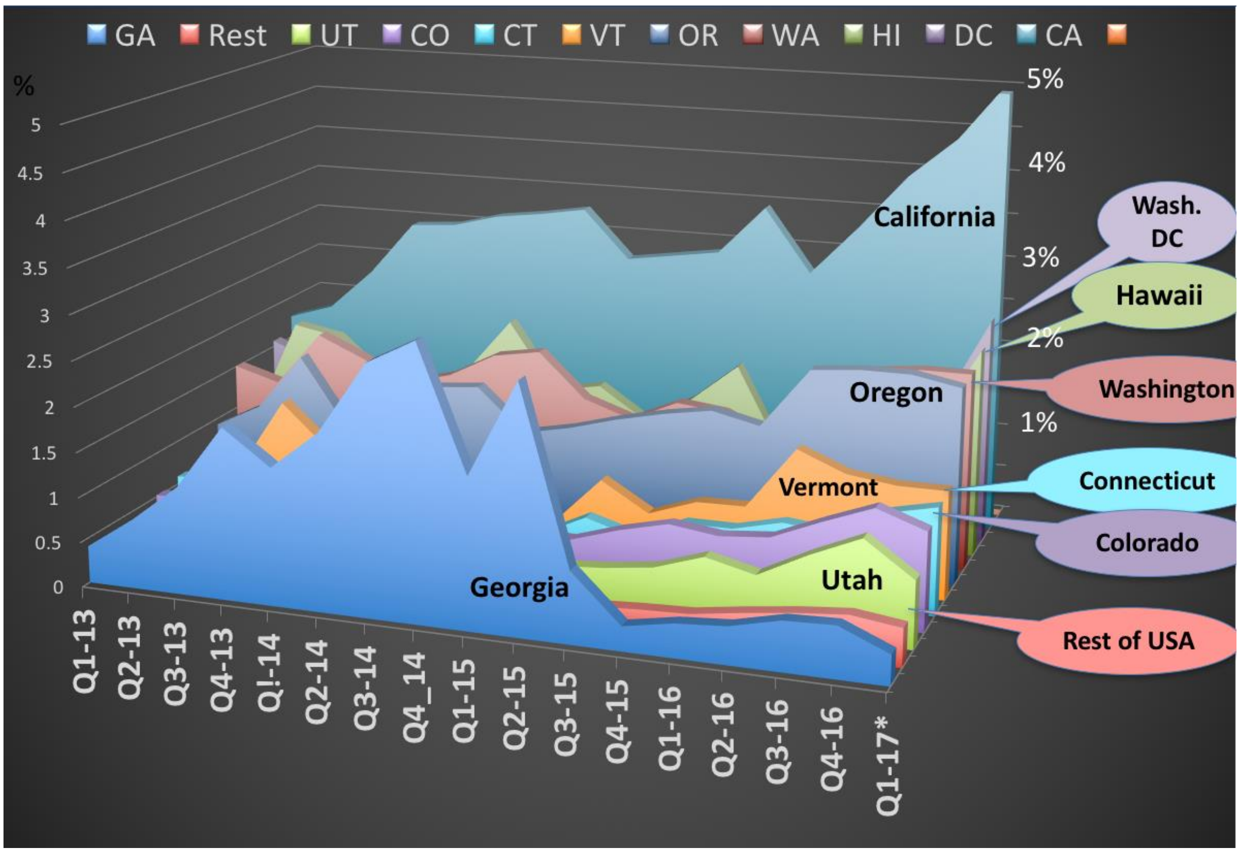

Figure 1. PEVs as a percentage of quarterly sales for light-duty vehicles in top ten U.S. states from Q1 2013 to Q1 2017.

In nations with high taxes on fuel and vehicles, there is an excellent pathway – the lowering of taxes on PEVs (Figenbaum 2016; Hoen & Koetse 2014; Jakobsson et al. 2016). This is the approach in Norway, Netherlands and Sweden. In the United States, where tax policy is limited, options are fewer and more controversial. In California for example, as the number of qualifying vehicles has increased, the pool of approved funds has been quickly used, requiring the legislature to allocate new monies with every budget cycle. In the early years, many of these rebates went to relatively affluent Californians, creating prickly social equity concerns. New rules apply an income cap for the incentives and allocate even more funds to potential buyers in disadvantaged communities in an effort to reset the incentive program priorities.

Over the course of 25 years Norway has developed a suite of incentives for PEV buyers that include among other things, lower taxes, access to bus lanes (connecting the suburbs to Oslo), and free parking (Figenbaum 2016). In California, a popular incentive to those who live and work in congested regions such as Los Angeles and the San Francisco Bay Area is single-driver PEV access to the HOV lanes (Tal & Nicholas 2014). Additionally, Norway grants free access over its many bridges and ferries. Unfortunately, these type of access rights get saturated in a few years.

In all these early markets, the challenge will be to keep incentives in place until the entire ecosystem of PEVs is in place: infrastructure, full rollout of vehicle types, costs of PEVs—primarily batteries—come in line with costs, and sales of PEVs reach a sustainable level, perhaps 10–15%. The time frame for this in California is around 2025. While Norway reached 30% of the annual market in early 2017 with its suite of incentives, the only other market beachheads that come close to that percentage are cities in coastal California and China, both about 10–15%.

The Charging Challenge

PEV charging infrastructure presents a different set of policy challenges (Gnann et al. 2016; Dunckley & Tal 2016; Xydas et al. 2016; Schäuble et al. 2017; Jakobsson et al. 2016). The primary challenges are to place chargers in optimal locations where demand is high and to provide equipment that meets the power needs of the users at that location. These locations can be homes, apartments and hotels where cars are often parked overnight, workplaces where cars are parked for many hours, shopping malls where users are parked for a few hours, and stops on long trips where users will want to charge in a few minutes. Users will include PHEVs with small batteries that can charge at lower power, as well BEVs with large batteries and that drivers may want to charge very quickly to get back on the road. Charger power can range from relatively low (3 kWh per hour) that takes hours to charge even small battery packs in PHEVs, to very high (300 kWh per hour), which can charge large BEV batteries in a few minutes. Moreover, the biggest challenge will be to roll out chargers at a rate that meets the hoped for 30–40% annual growth of the PEV market.

The best place to charge a PEV is at a location where it is parked for several hours (Nicholas et al. 2016; Hardman, Tal, et al. 2017), either at a home in a driveway overnight or a workplace near a potential plug or specialized charger. So far, most PEV buyers in the beachhead markets have been affluent homeowners (Hardman et al. 2016; Hardman & Tal 2016; Jakobsson et al. 2016; Tal & Nicholas 2013), who have good locations to charge at work or at home. In most cases, homeowners either make do with existing plugs or pay to install a charger. Many studies show that most charging—as much as 60–80%—occurs at home. To enable trips that are longer than the range of the vehicle, high-power chargers must be installed along highways, at special stations, restaurants, hotels, and other desirable destinations. These will extend the practicality of PEVs and increase the percentage of travel that PEV owners undertake using only electric drive, the ultimate goal of all policy.

However, as the market expands to drivers with less resources and to dense urban markets, many potential buyers live or work in locations where their car is parked on the street, in rented or multiunit dwellings, and at workplaces at which they have less control over installing a charger. These drivers need faster, higher power chargers that take minutes rather than hours to charge on their way to work, school, church and shopping. These drivers probably have fewer vehicles per household, especially outside the U.S., meaning they rely entirely on a single vehicle to accomplish all travel.

Public networks are owned and managed by automakers (e.g., Tesla), special charging network providers (e.g., Chargepoint), PEV owner clubs (in Japan), power utilities (in Ireland and other parts of Europe) as well as independent providers at workplaces and other destinations such as shopping malls. It will be years before these experiments settle into a system for all PEV parking and travel patterns, PEV types and battery sizes. So far, few charging provider companies are making profits from the sale of electricity at these chargers. Moreover, many public chargers are free to use. Partners have to work together to identify opportunities and challenges, and to stay ahead of congestion in the system. In the absence of a strong market signal, policy must make it easy and attractive for the needed charger types to be installed in locations that are convenient to many types of BEVs and PHEVs, which have a variety of demands.

PEVs are only as low carbon as the electricity they use (Tamayao et al. 2015; Axsen et al. 2011; Onat et al. 2015; Kelly et al. 2012). Norway, the poster child for electric drive policy, has very low-carbon electricity; over 95% is hydroelectric and the rest is wind. France's electricity supply is mainly low-carbon nuclear. Brazil's electricity is largely hydroelectric. Within the United States, however, there is great variation in the electricity supply, with over 2,000 electric utility companies, each with a different carbon footprint. An electric vehicle driven in the Northwest is lower carbon, given the higher percentage of hydroelectric capacity in that area. Many Midwest states rely on electricity generated from older coal-fired plants. California is a complex mix of natural gas, hydroelectric, nuclear, wind, solar and geothermal, with lots of regional variation. Despite the variation, on average, driving a PEV on electricity today in the U.S. is equivalent to driving a conventional vehicle that gets 80 mpg.[4] The good news here is that in many places, especially PEV beachheads, like China, California, France and Sweden, the percentage of low-carbon electricity is growing rapidly, with increasing use of solar and wind. During a few hours in May 2017, Germany announced that it had reach 80% renewables in that period – a record made possible by commitment and sophisticated management of the resources.

Timing is Everything…

To plan policy, we have to visualize the process of PEV market development as clearly and with as much science as we can bring to bear on what is an uncharted adventure through complex territory. It is important for policy makers to stay focused on the moment in this adventure when production costs of PEVs get close to parity with conventional combustion and hybrid

[4] https://blog.ucsusa.org/dave-reichmuth/new-data-show-electric-vehicles-continue-to-get-cleaner

vehicles. That is when the motivation of makers, sellers and consumers can align for massive changes in investments.

Policy to Support Generations of Technology and Market Development

Typically, a car maker develops technology over several generations of design, with the goal of improvement, reliability, customer feedback, parts chain development and cost reductions. For transformative technology changes involving HEVs, PHEVs and BEVs, there are many unknowns; mass production, sales and profitability are perhaps generations away and uncertain. Each generation lasts a few years, four to six years is common. As the technology evolves from first, to second, third and fourth generation rollouts, and as volumes grow from a few thousand conversions in the first generation, to tens of thousands in the second, and finally full mass production in the third generation, policy must support each step.

The first generation of PEV commercial sales (not counting pre-commercial sales test vehicles) often begin with a few thousand "conversions" of an existing model (often called a mule in the industry). Although they were not conversions in the true sense of the word, the Chevy Volt and Nissan Leaf in 2010 are examples the next step first-generation commercial vehicles. Such first vehicles can be a bit rough around the edges and are sold (often leased) to a first group of enthusiast consumers willing and able to take risks. Makers are engaged in an experiment at this phase, collecting extensive data on the vehicle and driver use patterns. Makers limit distribution to a few locations such as California or Norway that offer the most financial support and concentrate vehicles to simplify the support logistics as well. At this stage, policy makers are primarily targeting support to car makers who are limiting risks.

A second generation (for simplification, this generation for the begins around 2015–16) draws upon lessons from the first. Some makers will roll out a more attractive body and platform to optimize the electric drive. The second generation PEVs will minimally be a refinement of the first generation, usually with greater range, better interiors and performance. Third-generation PEV designs (again for simplification we estimate 2019–21) are the phase in which makers further refine their designs to meet market demands, to compete fully with conventional vehicles. They begin mass production in earnest, roll out to less subsidized locations, have a full chain of reliable parts ready for production, and focus on cost reduction in parts and manufacturing with the goal of making profits.

This third generation is perhaps the most critical moment for policy support, especially given climate goals. This is when volumes must move from a few percentage points to double digits, and success must be complete. Sales need to reach mass production goals, in the hundreds of thousands for each model, something that is difficult with even launches of conventional vehicles. Policy must not only encourage automakers, but also retail sellers and everyday consumers, and must stress that this is the automotive future.

Generations of Policies, Vehicles and Buyers

The rollout of the first generation of HEVs, the Toyota Prius and Honda Insight, began in Japan in 1997, and in the U.S. in 2001. In 2005, Toyota rolled out the second-generation Prius, and in 2010, accelerated production on the third-generation HEV. The world recession in 2008, however, upset sales, especially in U.S. Japan introduced subsidies on HEVs to boost sales in Japan. This strategy was very successful and annual sales of the third-generation HEVs climbed from a few percentage points to over 20% in a few years. Dan Rutherford of ICCT notes that a suite of subsidies in Japan that began in 2009 and were repeated after the tsunami in 2011 were more effective than predicted. They included tax subsidies and targeted sales subsidies; an example calculates $1,800 in tax breaks and $1,000 in subsidies for a $25,000 2010 Prius. HEVs rose to 32% of total vehicle sales in 2016. Total sales of all vehicles in Japan in 2017 equaled 4.1 million vehicles.

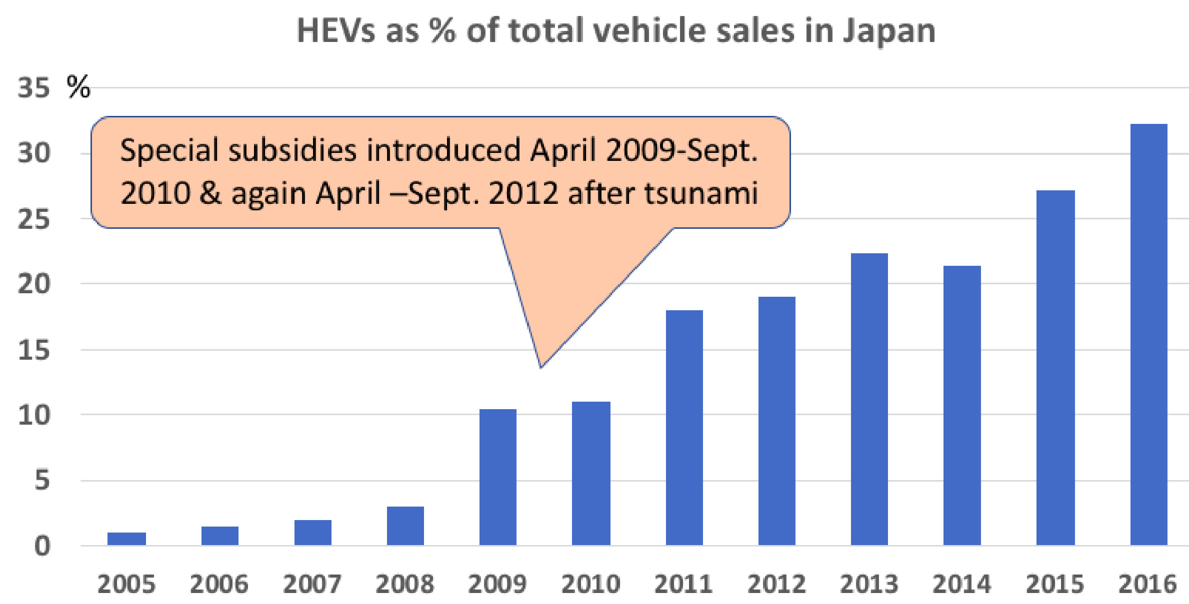

Figure 2. The growth of HEV sales in Japan. Source Japan Automobile Dealers Association and ICCT, Dan Rutherford

Inspired by the Japan HEV story and California's ZEV program as well as the initial history of the PEV market in California, Figure 3 illustrates the five-year "generations" of technology, policy and sales. The timeline begins with first generation commercial sales of lithium battery vehicles in 2010–2015, moves into the present second generation, and outlined the future third and fourth generations of vehicles, policy goals and consumers. This chart does not include used PEV sales, infrastructure rollout, or greening of electricity.

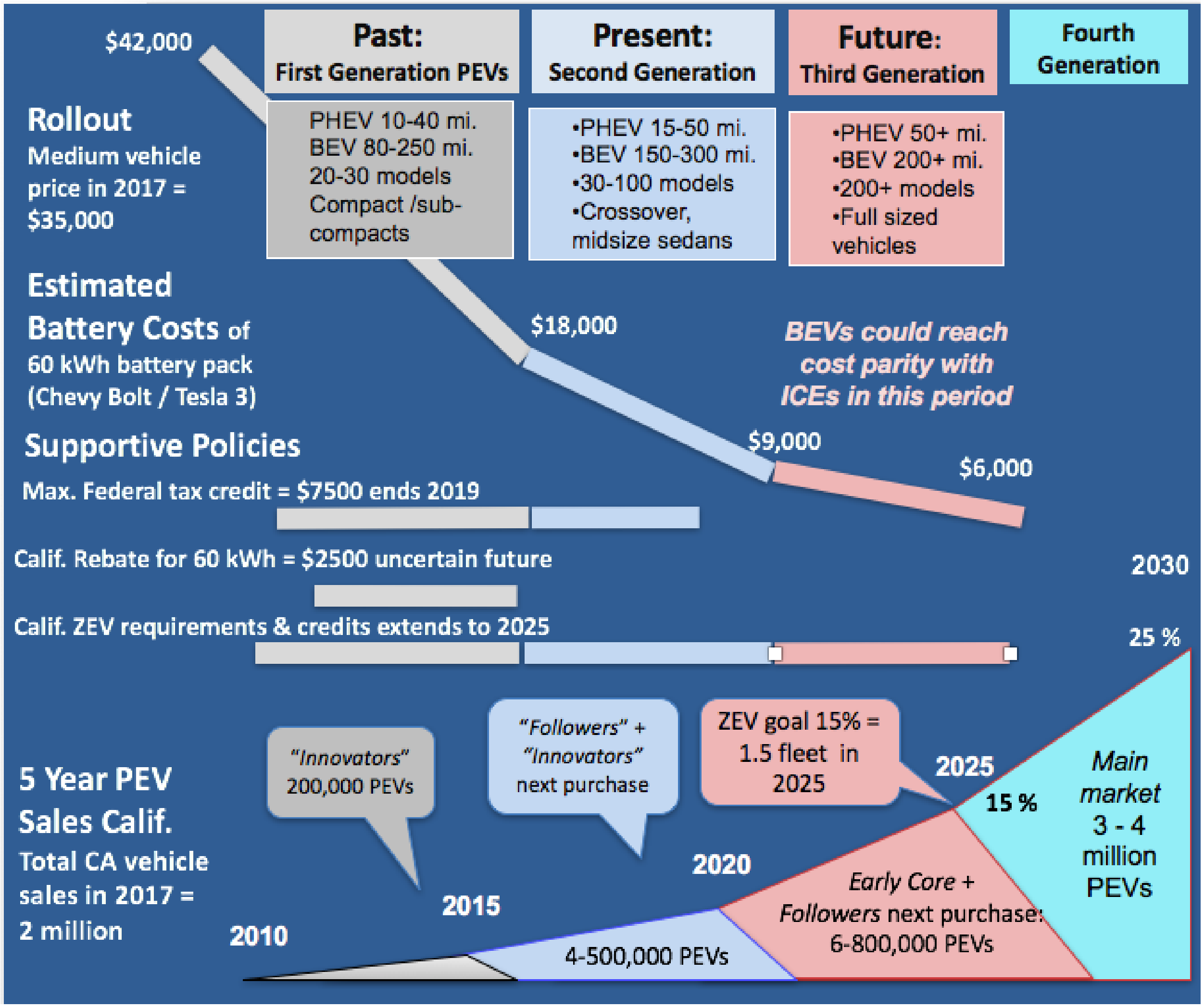

Figure 3. Charting the California PEV market from 2010 to 2030, past, present and future

Summary

To achieve carbon reduction goals for 2040 and 2050, PEV policy must be worldwide and involve multi-decade policy programs including:

- A broadening commitment to ending fossil fuels for light-duty vehicles; this will solidify the direction and accelerate investments in ZEVs and decapitalization of internal combustion drivetrain production so as to enable the climate driven timetable of the transition.
- Up to two decades of financial signals to buyers and producers, sized to keep the market tilted toward PEVs while production costs decline. Additional privileges in road, parking and electricity systems are needed to attract more conservative segments of buyers and sellers.
- PEV manufacturers committed to at least three generations of PEV design, and investment and product rollout into all market segments and vehicle designs.

- Outreach and education campaigns lasting through those three generations of potential consumers, including leveraging the enthusiastic desire of the first few million buyers to educate coworkers and neighbors. Inclusion of energy transitions in the education system is also necessary.
- The retail sector, primarily dealers included in the policy, education, and incentive programs.
- Coordinated efforts of OEMs, governments and power companies to meet charging needs and wants of the expanding market. This will need to include the greening of the grid and integration of PEVs in the system optimization of renewables.

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