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LITERATURE REVIEW ON POWER UTILITY BEST PRACTICES REGARDING ELECTRIC VEHICLES

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EXECUTIVE SUMMARY

As zero-emission vehicles (ZEVs) continue to grow in popularity, governments around the world are working to promote uptake and increase the benefits they hold for drivers and the environment. While a successful transition to a ZEV fleet will require the collaboration of many stakeholders, the role of the electric utility is especially important. As primary fuel providers, utilities can shape electric vehicle charging behavior and improve access to charging infrastructure. They can also influence the carbon intensity of the power source, and therefore, of electric vehicles.

High penetration of ZEVs, including plug-in and fuel cell electric vehicles, will also have a substantial impact on utilities, adding significantly to the electrical load and providing new business opportunities. Many utilities and governments have worked proactively to study the impacts of plug-in electric vehicles on the grid and the best ways to incorporate these vehicles into their future plans. Hydrogen fuel cell vehicles similarly offer an opportunity for utilities looking to engage with, and take advantage of, a changing transportation sector. Around the globe, different energy market structures and government actions have led to a wide variety of utility programs that support and adapt to ZEVs, and a number of trends and best practices have begun to emerge across jurisdictions.

This literature review summarizes practices among electric power utilities to promote the integration of electric vehicles and maximize their potential benefits to utilities, drivers, ratepayers, and society at large. Based on our review, we draw the following key lessons on utility best practices and mention examples where such efforts are in place:

> ***With proper planning, electric vehicles’ benefits to utilities outweigh their costs.*** It is clear that without any planning or preparation, high electric vehicle uptake could put significant stress on the electric power system and increase maintenance costs. However, with proper planning, transportation electrification can result in more efficient and less costly operation of the grid, provide ancillary services, lower electricity prices for ratepayers, and facilitate greater integration of renewable energy resources.
>
> ***Rate structures can influence electric vehicle charging behavior and grid impacts.*** Research has shown that restructuring electricity prices can influence consumer charging behavior and reduce electric vehicle fueling costs. Time-of-use rates, which offer lower electricity prices during off-peak hours, have already been successfully implemented in many jurisdictions, including California, New York, Maryland, and Germany. More complex systems, such as dynamic pricing, offer even greater benefits to consumers and utilities—such programs may also require smart meters and increased consumer involvement. In contrast, inclining-block tiered rates and capacity-based demand charges tend to present additional, but not insurmountable, barriers for electric vehicles.
>
> ***Smart charging can unlock the full benefits of electric vehicles.*** Although electric vehicles are designed for mobility, their energy storage capability is an important asset, especially as wind and solar power become more abundant. Smart charging allows utilities to effectively use this storage capacity to stabilize the grid and lower net costs, creating savings that can be passed on to electric vehicle owners directly and to all consumers through lower rates. One-way smart charging technologies are nearing commercialization (e.g., in California and the

Netherlands), and two-way vehicle-to-grid charging is an active area of research that could provide even greater benefits.

Greater regulatory clarity and standardization is needed. Uncertainty about vehicle-grid integration and electric vehicle infrastructure regulations and standards may discourage utilities from engaging with electric vehicles. Regulations regarding utility ownership of electric vehicle supply equipment (EVSE) vary greatly among jurisdictions. While power companies in areas such as Québec and parts of Europe have been instrumental in building charging networks, distribution operators in countries like the United Kingdom and Germany are not permitted to own such infrastructure, and regulations in many U.S. states remain unclear regarding utility ownership and operation of EVSE. In nearly all markets, confusion over EVSE hardware and software standards has been a barrier to lower equipment costs and the use of smart charging, although programs in the Netherlands and in Germany have made progress in this area.

Utilities can play a role in advancing the hydrogen economy. The fueling of hydrogen fuel cell electric vehicles is a fast-growing area of research and could present major benefits for utilities and drivers. Power-to-gas programs (e.g., in Germany) enable the use of excess renewable energy to generate hydrogen through electrolysis. Utilities, especially those that supply natural gas, may also have opportunities to invest in hydrogen distribution, storage, and even fueling infrastructure in order to diversify their business and support clean vehicles, although regulations on this subject are still evolving.

Although these lessons apply generally in many settings, the roles for different actors will vary according to energy market structure and regulations, generation portfolio, government policies and priorities, and other factors. This report discusses many such regional differences. In many cases where utilities are most productive in promoting electric vehicles, they collaborate closely with other stakeholders, including automakers, software companies, and research institutions, to tackle their own unique challenges.

Research projects will continue to further define the best models for utility investment in deployment of charging infrastructure, smart charging, and integration with renewables. More research is still needed, particularly in how smart charging and vehicle-to-grid technologies can benefit drivers as well as utilities at different levels of the electrical system. Nonetheless, several programs are already close to widespread implementation and could make strides towards achieving climate goals and grid stability. The area of vehicle-grid integration and utility support for ZEVs is still maturing. But with regulatory incentives for the deployment of charging infrastructure and policies that encourage the use of EVs acting as distributed energy resources, utility engagement with ZEVs can lead to a more stable grid, new business opportunities, and cleaner, more affordable vehicles with increased value for society and the environment.

I. INTRODUCTION

Over the past decade, electric vehicles have made remarkable strides, transitioning from a niche technology into a small but growing part of the transportation landscape. In 2015 and 2016, electric vehicles accounted for a significant share of new car sales in leading regions, including 23-29% in Norway, 6-10% in the Netherlands, and over 5% in various markets across China and California (EV sales, 2017; Lutsey, 2017; Searle et al., 2016; CNCDA, 2016). Although electric vehicles still lag behind conventional vehicles in sales, improved battery technology has led to significantly increased range, shorter charging times, and a continuing decline in costs.

In addition to reducing air pollution, oil consumption, and greenhouse gas emissions, transportation electrification offers other benefits, including a substantial new business opportunity for electric utilities. While many utilities have not substantially engaged with the technology, interest in utility transportation electrification programs has grown considerably in recent years. Utilities and other stakeholders have launched numerous studies and research projects from which several trends and best practices have emerged. More broadly, utilities could play a key role in promoting and facilitating the transformation of our transportation sector away from petroleum-based fuels.

This paper provides an overview of the existing research and analysis of the intersection between utilities and ZEVs. The paper reviews literature produced by researchers, utilities, and government agencies to help catalogue utility practices that support the growing ZEV market. The topics discussed include the impact of electric vehicles on the grid, utility support of transportation electrification, smart charging technologies and their effects, and novel business models in this field. Exemplary programs and best practices are identified, as are areas of uncertainty and opportunities for future research. This review includes programs from around the world, but primarily focuses on selected regions of North America and Europe.

This topic is important for the future of transportation electrification because utilities have the ability to influence the developing market in a positive way through the implementation of rate policies that benefit consumers, outreach and education programs, investment in charging infrastructure, and utility lead-by-example programs. Utility policy can help to accelerate electric vehicle adoption in ways that ultimately benefit the grid and all ratepayers. As ZEV uptake continues to increase, the impetus for utilities to capitalize on these technologies will only grow. By learning from the numerous trials, simulations, and studies already conducted, electric power companies and governments can pursue programs that maximize benefits to all stakeholders.

II. OVERVIEW OF THE ELECTRICAL SYSTEM

Before reviewing literature on integration of vehicles into the power grid, it is important to understand the electricity system and its regional variations. On a fundamental level, the system is divided into four stages: generation, transmission, distribution, and retail. Generation traditionally consists of creating electricity in large quantities at centralized power plants, which is then fed into the electrical grid. During transmission, electricity is carried at high voltages of greater than 100 kilovolts (kV), via alternating current (AC) or direct current (DC), over long distances from power plants to cities and towns where it will eventually be used. The distribution system sends power at lower voltages to the final customers, including homes, businesses, and factories. Finally, in the retail phase, customers are metered and billed according to their use, and retailers work with the grid operators to ensure that the supply is reliable and sufficient.

Although this basic structure is essentially the same across the world, there are technical differences among various electricity grids. In the United States, most of Latin America, and Japan, household electrical service uses 120-Volt (V) and 60-Hertz (Hz) AC power, while the rest of the world (including all of Europe, China, and Oceania) uses 220 V/50 Hz power. Current limits in typical household circuits also vary, from 13 amps (A) in the United Kingdom to 15 A in the United States and 16 A or above in Germany (Jundel, 2015). Variations such as these can affect the costs of EVSE installation and the infrastructure needed to adapt to electric vehicles.

Defining and comparing utilities. Which entities exactly are referred to as utilities is an important distinction. In the broadest sense, any company that operates infrastructure for generating or transporting electricity can be referred to as a utility. Most commonly, however, the term “utility” denotes the organization responsible for the infrastructure at the distribution or transmission stages; we adopt this definition throughout this paper. While customers rely on their utilities to access electricity from the grid, the utilities may not always determine how the electricity is generated or the rates at which it is sold. Other entities influential in electric vehicle programs may not fit this stricter definition and may be referred to by different names in this paper—for example, “power company” as used here refers to a company that owns generation assets but does not necessarily distribute electricity, while a “retailer” may sell electricity and set rates but not own any physical infrastructure.

Utilities may participate in one or more stages of the electric power system based on their local regulations and markets, and a given region may have any number of utilities. Figure 1 shows an illustrative diagram of the concentration of utilities at the generation, transmission, and distribution stages for three representative markets: New York, Québec, and Germany. The number of points in the figure represents the number of major actors at each stage for each of the markets. Perhaps the simplest utility structure is vertical integration, in which one utility controls all generation, transmission, distribution, and retail for a given region. This is shown in the middle column of Figure 1, which represents the structure of utilities such as Hydro Québec. Until the 1990s, this model was standard across North America and Europe. Some incumbent vertically integrated utilities in Europe, such as EDF and Vattenfall, still maintain small stakes in many different parts of the electrical system, but their roles have been limited through unbundling. Today, vertically integrated utilities still have complete monopolies in parts of North America, including the provinces of British Columbia and Québec in Canada and U.S. states such as Georgia, Florida, and Arizona (NAS, 2015). China uses a similar system. As illustrated in the figure, electric utility systems have evolved in different ways, sometimes with many more generation companies (e.g., in New York), and others many more distribution networks (e.g., in Germany).

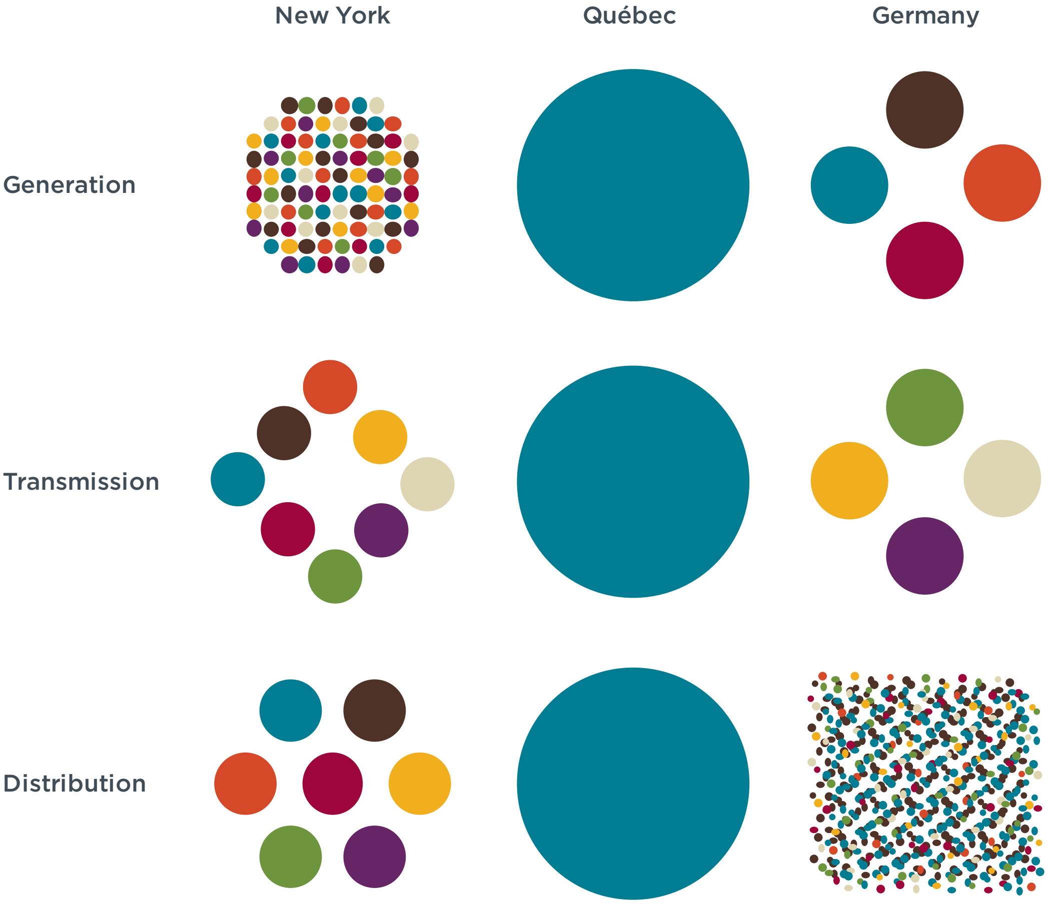

Figure 1. Schematic of the concentration of utilities at the generation, transmission, and distribution levels in three representative regions

Over the past several decades, many utilities in North America and Europe have undergone deregulation (also known as restructuring) to separate their generation, transmission, distribution, and retail businesses. In order to match supply and demand among the many players in a deregulated market, wholesale markets allow power to be purchased, both far in advance and in real time. Wholesale markets can be exclusive to a single jurisdiction (such as in California or the United Kingdom) or shared among partners (like the six New England states; the EPEX SPOT market shared by Germany, France, Austria, and Switzerland; and the Nord Pool Spot market shared between the Nordic countries) (NAS, 2015; M.J. Bradley, 2013). Even among deregulated utilities, the number of generating companies, network operators, and retailers can vary greatly, as indicated in Figure 1 (left and right columns).

Although the best-practice programs discussed in this paper can be implemented in a variety of markets, the structure and level of regulation can affect how programs are designed and which companies are most likely to participate. In general, those utilities with multiple lines of business and large service areas have greater resources and flexibility to launch major research projects and deploy extensive charging networks.

However, smaller municipal utilities may be more capable of analyzing the specific needs of their communities to provide appropriate grid upgrades and rate options. Similarly, while vertically integrated utilities may see a greater boost in revenue from electric vehicles, some grid benefits resulting from vehicle-grid integration may have the most impact at the distribution level. This indicates that players at any level of the power system have motivation to proactively plan for transportation electrification, depending on local regulations regarding infrastructure ownership and how utilities can earn revenue.

Ancillary services. Although electric vehicles increase the total load on the power grid, they have the potential to benefit utilities by providing "ancillary services" that maintain grid stability and prevent outages during unexpected circumstances or high demand periods. The specific terminology used for short-term ancillary services varies among markets, but these services generally include frequency response (typically called primary regulation in Europe), which entails injecting power or curtailing demand within a few seconds of a power disruption to stabilize grid frequency and voltage, and regulation services (secondary regulation in Europe), which will activate over a period of a few minutes and last up to 30 minutes to accommodate unexpected demand (M.J. Bradley, 2013; Schuller & Rieger, 2013). Additional ancillary services include spinning reserves, which serve as backup generation in case of equipment failure, and black start services, which help to restore service in case of total power outages; however, electric vehicles are less suited to provide these because of the need for large, sustained power outputs. In some jurisdictions, there are additional grid services at the distribution level that could be fulfilled with vehicle-grid integration (see Langton & Crisostomo, 2014; Schuller & Rieger, 2013). As increased renewable energy generation leads to greater variability in the electricity supply, the ability of electric vehicles to balance loads and support grid voltage and frequency with these services will become even more attractive.

Most grid operators allow frequent, competitive bidding to provide ancillary services, although details (such as minimum power and duration of services required to bid) vary among markets. This market system, which is common within the United States and is encouraged by policymakers in European Union, appears to be most conducive to realizing all of the possible grid benefits from electric vehicles (M.J. Bradley, 2013). In a few more recently deregulated markets (particularly in Europe), transmission system operators negotiate contracts for the provision of ancillary services directly with generators, while in the classic vertically integrated utility model, ancillary services are typically procured from the utility's own generation resources (Eurelectric, 2004). In both of these cases, it is more difficult for groups of electric vehicles to supply ancillary services than in an open market.

Table 1 summarizes a number of key features in five markets and helps illustrate differences among major markets' power systems. The varying numbers of actors across markets will require different regulatory approaches and business models: For example, the large number of distribution system operators (DSOs) and retailers in Germany suggests that it will be relatively difficult for consistent, large-scale programs (e.g., aggregation of large numbers of smart-charging vehicles or planning for inter-city charging networks) to be implemented at the distribution level, meaning that other organizations may have to take stronger roles. In contrast, the vertically integrated structure in Québec means that its utility will likely have greater flexibility in organizing comprehensive transportation electrification programs.

Table 1. Characteristics of electric power utility structure for selected electricity markets in select jurisdictions

	California	New York	Québec	Germany	United Kingdom
Number of generation operators	527	94	1 primary	>1000	6 primary
Number of TSOs	6 primary	8	1	4	1
Number of DSOs	5 primary, 51 total	7 primary, 48 total	1 primary	890	6
Number of retailers	76	71	1	>1000	40
Wholesale market	CAISO	NYISO	None	EEX	National grid
Ancillary services market	CAISO	NYISO	Centrally controlled	Bilateral tenders	National grid
Smart meters	Yes	In progress	In progress	Planned	Planned

TSO = transmission system operator; DSO = distribution system operator (referred to as DNOs in some jurisdictions); EEX = European Energy Exchange; NYISO = New York Independent System Operator; CAISO = California Independent System Operator

Power generation portfolio. In addition to differences in market structure, different regions have vastly different energy mixes, which can in turn affect utility perspectives on electric vehicles. While this has received significant study with regard to the total CO_2 emissions from electric vehicles, a region's power generation portfolio can also influence the needs and opportunities for integrating electric vehicles into the grid and the types of services that electric vehicles can provide.

Figure 2 illustrates the electricity grid mix (stacked bars, left axis) and the corresponding carbon intensity (grey line, right axis) from electricity generation in selected markets (based on Ecofys, 2014; ENTSOE, 2015; IEA, 2015; U.S. EPA, 2015). As shown in the figure, some markets are dominated by hydroelectric power (blue bar), while others rely more on coal, natural gas, or nuclear as the major energy sources. The relative availability of baseload power plants (such as nuclear plants), "peaker" plants (such as natural gas combustion turbine units, which can quickly ramp up production but typically have higher CO_2 emissions), and intermittent sources (such as onshore wind and solar power) can influence the impacts of electric vehicles on the grid. Electric vehicle charging, which can quickly increase the demand for electricity, may require using more peaker plants unless charging can be managed. More flexible sources such as large hydro reduce this challenge, while inflexible generators such as nuclear, wind, or solar may exacerbate the problem, as excess capacity only exists at certain times of day. The operational types and carbon content of generation available therefore inform the optimal times to charge electric vehicles and the importance of scheduling charging. In most locations, this means charging during periods in the late night or early morning that are considered "off-peak" to avoid the higher costs of marginal "peaker" units, and during times of renewable over-generation conditions, such as around noon in areas with significant solar resources.

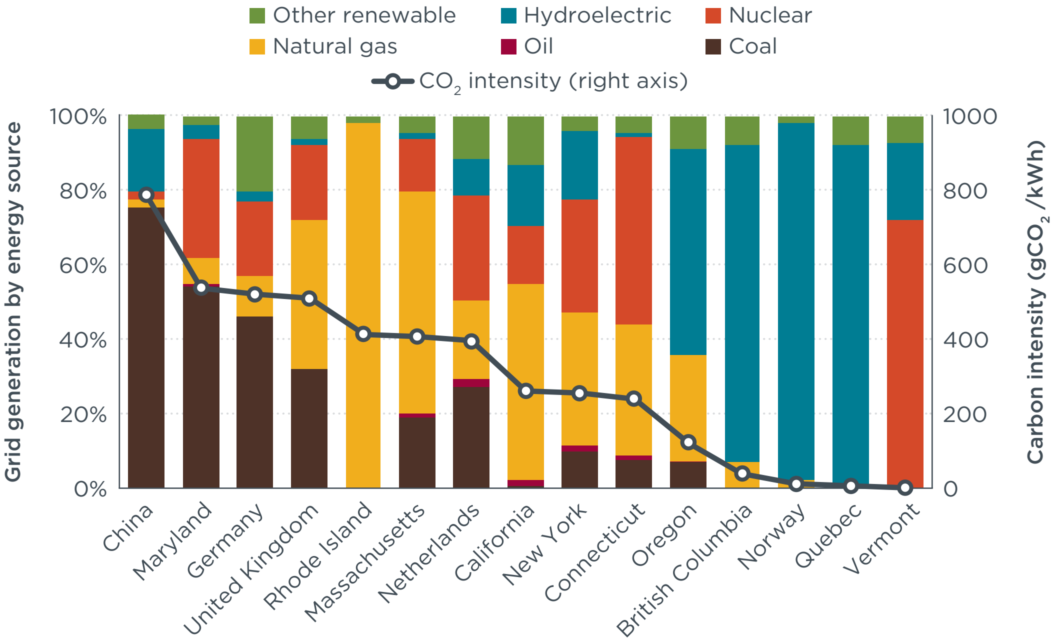

Figure 2. Grid generation energy sources and estimated carbon intensity for selected markets in 2013

In addition, a region's generation mix directly effects the environmental performance of electric vehicles. As shown in Figure 2, a higher percentage of renewable and nuclear power generation results in lower carbon dioxide emissions per kilowatt-hour of electricity generation (grey line, right axis). After including upstream impacts, electric vehicles typically result in substantially lower emissions than conventional vehicles (e.g., see EPRI & NRDC, 2015; Nealer et al., 2015; Lutsey, 2015; Wolfram & Lutsey, 2016). Developments in renewable generation technologies in combination with stringent application of carbon cap-and-trade programs, low-carbon fuel standards, carbon emissions regulation, and renewable generation quotas will further reduce the carbon intensity of electricity and therefore electric vehicles.

III. OPPORTUNITIES AND CHALLENGES FOR UTILITIES

ELECTRIC VEHICLE ADOPTION AND POTENTIAL BENEFITS

Although many in the electricity industry have been hesitant to proactively support electric vehicles, utilities stand to benefit greatly from increasing electric vehicle uptake over the coming years (E3, 2015). With proper planning, electric vehicles not only represent an important opportunity to compensate for energy efficiency requirements and stabilize demand, but also can provide valuable services to the grid and facilitate the transition to a smarter, more diversified electrical system, as described below.

Increased sales. In the United States and Europe, total electricity sales are projected to plateau or even decline in the coming decades, primarily due to greater energy efficiency and the spread of distributed power generation such as rooftop solar. The International Energy Agency's New Policies scenario projects growth in total electricity use of only 0.7% annually among OECD nations, even when including new demand from transportation electrification (IEA, 2015). This represents a substantial drop from previous decades—for example, growth in the same metric from 1990 to 2013 was over 27%. Electric vehicles represent a source of new demand that is likely to expand for decades to come: The Edison Electric Institute (a trade group for U.S. utilities) states that "bringing electricity to the transportation sector is a huge, albeit long-term opportunity for load growth" (2014). According to forecasts, a typical electric vehicle would use about 261 kWh per month, increasing a U.S. household's demand up to 40% (Salisbury & Toor, 2016).

This growth is perhaps even more important in Europe, where electric vehicles may be able to offset declines in electricity sales and balance an increasingly erratic load brought on by high renewables penetration. This could reduce the sunk costs faced by utilities and increase revenue, ultimately lowering rates for all consumers. Because of lower household energy use in most parts of Europe, electric vehicles represent an even greater percentage increase in electricity sales—reports estimate that an electric vehicle driven 15,000 km per year (using 3,500 kWh) would roughly double household energy use in the Netherlands or Germany (McKinsey, 2014; Bohn et al., 2015). This growth from transportation electrification, while significant, will likely occur gradually across the coming decades—some estimates show that total electricity consumption in some countries (e.g., Germany) will still decrease through 2050 because of significant energy efficiency improvements (Wünsch et al., 2014).

Grid stability. Although electric vehicles represent an opportunity to expand utility business, their greatest benefit to the grid lies in their flexibility and energy storage capabilities. Electric vehicles generally are only used a few hours of the day and are frequently left plugged in overnight (and throughout the day if workplace charging is available), but a full charge with a Level 2 charger requires about three to five hours. This could allow utilities to manage electric vehicle charging within this window to benefit the electricity grid. Because the ancillary services produced in this way are normally purchased by utilities, using electric vehicles for grid services could provide flexibility and savings for utilities even while providing valuable compensation to electric vehicle owners.

> **Peak shifting.** Because electricity demand is highest in the late afternoon and early evening when electric vehicle customers might normally plug in their vehicles after work, uncontrolled charging can result in additional peak demand, which can require

expensive distribution network upgrades and additional generation capacity. However, electric vehicle charging could be shifted to either late at night, when electricity demand and rates are the lowest, or during the day when solar power is most plentiful. Proactive programs would allow utilities to encourage electric vehicle charging at times when there is the most excess capacity, thereby adding sales while avoiding increases in peak demand. Some leading utilities (such as those in California) have already created effective programs to shift demand, as described in Section IV of this paper.

Demand response. With communication between electric vehicles and the grid, electric vehicle charging could be paused when demand spikes or there are disruptions in supply, preventing a drop in frequency. When demand drops or additional renewable resources come onto the grid, charging can be turned on. This capability, known as demand response (DR), has been demonstrated in many trials, both for public and household charging. A number of companies already sell DR-capable EVSE, although few utilities have programs to make use of such EVSE at this time.

A similar but more advanced idea is controlled charging, in which the power delivered to an electric vehicle can be not only switched on or off at specific times, but also increased or decreased in real time in order to reflect renewable energy supply, market prices, and grid stability. This more advanced practice is known as V1G, and although this program has yet to be implemented on a large scale and more sophisticated communications protocols would be needed, it requires only minimal new hardware and would not add stress to the vehicle's battery.

Vehicle-to-grid (V2G). Because electric vehicles store electricity in their batteries, it is possible to return power from vehicles to the grid when demand is highest. Using power from electric vehicles provides maximum flexibility to utilities, especially in helping to balance swings in supply due to renewable energy resources. If proper markets are in place (discussed in Section IV), selling this power to utilities could bring substantial financial benefits to electric vehicle owners, as well as reduce costs for utilities, who could avoid using expensive and dirty peaker power plants or building additional stationary storage.

This requires more complex vehicle and EVSE hardware, such as bidirectional inverters and two-way chargers. There have been mixed opinions about the effects of reverse charging on battery performance. Some estimates show that the benefits to the grid outweigh any additional battery degradation, and well-programmed V2G charging could even be beneficial to battery health compared to traditional charging patterns (Wang et al., 2016). V2G programs for groups of electric vehicles have been demonstrated in a number of fleet trials (with some examples in Section IV), but utilities and automakers are both hesitant to invest heavily in this experimental technology, creating a sequencing problem.

Battery second life. The exact lifetime of battery packs in electric vehicles is still uncertain, but even after the batteries' initial lifespan in the vehicle is complete, they typically still have about 80% of their original capacity. This represents a significant opportunity for stationary energy storage (Reid & Julve, 2016; Putrus et al., 2015). A study from the German Renewable Energy Association predicts that there will be more than 1 TWh of storage capacity from used electric vehicle batteries available by 2030, enough to power the entire United Kingdom for a full day (Reid & Julve, 2016). This storage capacity could address one of the greatest challenges of a renewables-based electricity system, as well as capture otherwise unused value from electric vehicles—estimates show values of approximately $100 per kWh for used batteries (Elkind, 2014). However, some automakers and scientists have concerns about the feasibility, cost-effectiveness, and even safety of battery second-life systems, suggesting the need for more research (see Neuber et al., 2015). While some trials are underway to study the performance of used electric vehicle batteries (discussed further at the end of Section IV), business models for battery second life and compensation to electric vehicle owners are still in their early stages. Regulatory issues regarding the connection of pilot projects to the grid and the risk of battery problems could also hamper implementation of second-life programs (Elkind, 2014).

POTENTIAL CHALLENGES

Although there are many benefits to successful vehicle-grid integration (VGI), there are still technical and logistical challenges for utilities adapting to a large number of electric vehicles. Anxiety about grid preparedness for electric vehicles frequently comes from the fear of thousands of electric vehicles being plugged in during evening hours after drivers arrive home from work, overloading local distribution transformers and adding to peak loads when energy is most expensive and carbon-intensive (NAS, 2015).

The degree of this problem depends on the specific distribution grid and the level of electric vehicle penetration. A trial by Xcel Energy in Colorado concluded that at electric vehicle market penetration of 5%, up to 4% of distribution transformers could be overloaded if all electric vehicles are charged during peak times (Xcel Energy, 2015). Similarly, in the United Kingdom, the My Electric Avenue project estimated that with 40–70% of cars electrified and using uncontrolled charging, 32% of distribution circuits would require upgrades (EA Technology, 2016). In California, the Sacramento Municipal Utility District projects that uncontrolled charging during peak hours would result in upgrade expenses of up to $150 per vehicle at electric vehicle uptake levels up to 5% (Berkheimer et al., 2014). Although these costs appear significant, they could be substantially reduced with greater utility planning and investment in VGI. Additional literature addresses various elements of grid preparedness in other regions and potential strategies for minimizing associated upgrade costs (e.g., see Bohn et al., 2015; E3, 2014; Neaimeh et al., 2013).

Beyond the financial costs of preparing the grid for electric vehicles, utilities can face legal and procedural obstacles as they try to participate in the electric vehicle sector and VGI. For example, while many competitive power companies in Europe have led the charge in installing public EVSE (e.g., RWE and EnBW in Germany, Fortum in the Nordic countries), utilities in parts of the United States face significant regulatory hurdles in building and operating charging stations. Even in jurisdictions that allow utilities to own EVSE, utilities have faced resistance and legal challenges for fear of hampering private-sector competition (Alexander-Kearns & Cassady, 2016). Additionally, some forms of smart charging and advanced rate structures require the installation of smart meters, which have faced public opposition in many areas and cost approximately $300 per customer (Wired Group, 2013). However, many jurisdictions are already installing smart meters as part of broader grid upgrade programs and see numerous other benefits to the technology, making them a prudent investment in many cases.

IV. BEST PRACTICES AND EXEMPLARY PROGRAMS

Because electric vehicles represent a substantial source of revenue and long-term growth, utilities have a direct incentive to support the adoption of electric vehicles. Utilities encourage and benefit from electric vehicle uptake in a number of ways, including by providing financial incentives for charging infrastructure, installing that infrastructure themselves, implementing smart charging, offering electric vehicle-friendly rate structures, forming partnerships with other stakeholders, and more. This section highlights a number of best practice and exemplary programs that are being implemented and tested around the world today.

REGULATORY ACTIONS

Utilities can support electric vehicles and advance their services in many ways, but in order to take these actions, there must first be a supportive regulatory environment. As utilities work to adapt to this growing market, governments can unlock benefits to electric vehicle owners and power companies alike by adopting the right policies and remaining responsive to new developments.

EVSE ownership regulations. As demand for electric vehicle charging stations grows, many utilities with generation or retail operations are investigating taking an active role in deployment and management of EVSE. In some areas, however, utilities are expressly prohibited from owning EVSE or restricted in how they can pay for such investments. In jurisdictions where regulations on utility ownership of EVSE have become less stringent (such as North Carolina and Oregon in the United States and Tokyo in Japan), utilities have built extensive charging networks (NAS, 2015). Encouraging such utility programs can be crucial in building charging networks, especially in areas that lack sufficient infrastructure.

Because utilities using ratepayer money to build EVSE face less pressure to make immediate profits on electric vehicle charging sales, there are concerns that large utility build-out may stifle private-sector competition (Alexander-Kearns & Cassady, 2016). On the other hand, the heavy regulation that many utilities operate under could cause them to develop EVSE more slowly than private-sector competitors in profitable areas. When utilities do own EVSE, it may be preferable to promote public-private partnerships and limit utility construction to cover only certain segments of the market, such as multi-unit residential buildings or workplace charging, that are less likely to be served by the private market alone (van Deventer et al., 2015; E3, 2014a). The California Public Utilities Commission (CPUC) has also considered this issue in three proceedings with California utilities seeking to build charging networks (CPUC, 2016a; 2016b; 2015). In the Netherlands, the government has created an open tender system for all public EVSE installations, where utilities and private companies can bid for local and European Union funding to improve charging access in specific areas, allowing governments to promote a variety of business models and actors (Lewis, 2015). Programs such as these could allow utilities to provide a valuable service to electric vehicle owners while also promoting competition and inventive business models.

Rate-basing electric vehicle investments. Utility investments in infrastructure to support electric vehicles, including system upgrades, dedicated meters, and workplace or public EVSE, could be funded by distributing the cost across all customers, a practice known as "rate-basing." Rate-basing investments adds only a small amount to customer electricity bills, and regulatory agencies may encourage these investments due to their potential to increase utilization of the electric grid and drive down rates for all ratepayers. Recognizing the benefits that electric vehicles bring to society through reduced emissions and pollution, regulators in California and Hawaii have approved rate-basing of EVSE expenses up to a certain level (Salisbury & Toor, 2015). Policies in other parts of the world are less clear, but explicitly allowing such financing would allow for greater flexibility in supporting electric vehicles.

Several U.S. utility programs provide an indication of how utility-financed charging infrastructure build-out might occur. Depending on their assets and regulatory framework, utilities may be motivated by the potential for transportation electrification programs to increase revenue, reduce rates, and manage grid loads (see Ryan & Lavin, 2015). As of mid-2016, several U.S. utilities have moved toward more progressive planning for electric vehicles, including deploying ratepayer-funded public charging infrastructure in order to accelerate the slow pace of growth in this sector. Kansas City Power & Light had the first major program of this kind; Southern California Edison, San Diego Gas & Electric, and Pacific Gas & Electric have such programs in place (SDGE, 2016; Edison International, 2016; CPUC, 2016a; 2016b); and Oregon has paved the way for the state's major utilities to build infrastructure (KCP&L, 2015; CPUC, 2016e; Pacific Power, 2017). Missouri utility Ameren has submitted a similar proposal for approval, indicating significant expected growth of electric vehicle infrastructure in that region (Muehlenkamp, 2016). These programs are widely viewed as initial steps to build out charging infrastructure and help determine the best practices for long-term network growth. They tend to differ in their scale, relationship with third-party EVSE providers, specific charging circumstances (e.g., home, workplace, multi-unit dwelling, etc.), and how electric vehicle charging rates are determined. In all of these U.S. examples, however, regulators have only allowed a pre-determined number of charging stations, indicating that they are hesitant to let utilities fully control the market.

Electricity market structure. As previously noted, a wide variety of electricity market structures exist in different regions, ranging from fully integrated wholesale markets (such as in California and the United Kingdom) to no market at all in vertically integrated jurisdictions (such as Québec and parts of the U.S. Southeast). Many countries are already working to create and modernize electricity markets to prepare for distributed generation and reduce costs for consumers, and regulators may want to consider such moves in light of VGI initiatives.

Services such as frequency regulation and spinning reserves (secondary regulation) are most important in realizing electric vehicles' grid benefits and providing incentives to electric vehicle owners, so allowing open trading of these services rather than bilateral contracts could provide substantial benefits to utilities and electric vehicle owners alike. In order to create aggregations of electric vehicles that are dispatchable and reliable, it is important for grid operators to craft policies enabling aggregations of vehicles and distributed energy resources (DERs) generally—such efforts are underway by the California Independent System Operator (CAISO), which manages the state's power grid (Langton & Crisostomo, 2014). This advancement also requires incorporation of metering and communications technologies within vehicles and EVSEs. Reducing the minimum power requirements and allowing aggregation across multiple meters can further lower the barrier to entry; for example, PJM's new 100 kW minimum (which can be added across multiple meters) allows a group of as few as nine electric vehicles to bid onto the market and provide services through an aggregator, and National Grid in the United

Kingdom has created Firm Frequency Response Bridging Contracts to improve access to the ancillary service market for smaller providers (Markel et al., 2015; National Grid, 2015). Finally, it is important for utilities, regulators, and private sector partners to create distributed-generation aggregation platforms or provide support for third-party aggregation businesses to make VGI a reality and work towards a cleaner, smarter grid.

Encouraging utility investment in VGI through revenue regulation. In most markets, utilities are regulated in order to encourage fair practices and low rates for consumers. This has resulted in a number of regulatory frameworks designed to promote energy efficiency and higher quality of service rather than maximize electricity sales, such as price caps and revenue caps. As the grid changes and utilities seek to promote electric vehicles, it is important that revenue regulations be designed to encourage DERs and vehicle-grid integration practices that benefit ratepayers and the environment.

Regulatory frameworks in U.S. states such as California and New York require special consideration in regards to transportation electrification. In these systems, a form of revenue caps, utility rates are designed to recover operational expenses and capital infrastructure investments, such as generation plants and distribution lines, regardless of sales volumes. While this incentivizes maintaining and upgrading the grid, it actually discourages utilities from investing in DER programs (especially electric vehicles, which they would not own), as these would delay the capital expenditures that lead to revenue (CPUC, 2016c). Some potential ways to address this quandary include compensating DSOs for publishing information about and providing access to the distribution system, splitting revenue for vehicles participating in electricity markets, allowing utilities more flexibility to determine location-specific feed-in rates, and providing a rate-of-return on software and DERs (SCE, 2016). Additionally, it is important to carefully consider policies regarding electricity sales from EVSE, as traditional regulation may make charging networks less profitable or encourage construction of more expensive, rather than the most useful, EVSE.

Defining standards. Because electric vehicle technologies (especially VGI applications) are still emerging, state-of-the-art technology evolves quickly and standards are often poorly defined or vary widely among regions. This uncertainty can discourage investment from utilities in programs that fall outside of their traditional business model. Clear guidance from regulators will not only allow utilities to offer solutions with confidence and collaborate with other stakeholders, but also lead to a more unified system for electric vehicle customers.

A few utilities and EVSE companies in Europe, especially in the Netherlands and Germany, have advocated for communications standards to allow interoperability and "e-roaming" between charging station networks, leading to the wide adoption of the Open Charge Point Protocol (OCPP) and Open Clearing House Protocol (OCHP) in many countries (Bakker & Trip, 2015). This has resulted in a number of international projects, such as Ladenetz, a collaboration between municipal utilities in Germany and the Netherlands, universities, and private EVSE operators, and Hubject, a private company supported by German power companies RWE and EnBW. The multiple international programs within Europe cannot currently work together, but European Union policymakers hope to unite these efforts with common standards (Green eMotion, 2015). Governments in other regions, including the United States, have been less progressive in creating unified software and communication standards for electric vehicles, although CPUC has recently recommended communications standards for all utility VGI programs in California, with the support of several automakers (CPUC, 2016c). Additionally, the recently founded ROEV group, which includes original equipment manufacturers (OEMs), EVSE manufacturers, and the Oregon utility Portland General Electric, is working to introduce a consistent, simple payment scheme to all charging networks in the United States (ROEV, 2015). As smart charging becomes more common, new standards will require increased collaboration among utilities, EVSE manufacturers, and OEMs.

Notification. In order for utilities to properly plan for electric vehicle-related system upgrades and take advantage of potential grid benefits, it is imperative that utilities know which residents own electric vehicles and how they will be charged. As of mid-2016, however, there is no set protocol for alerting utilities of new electric vehicles registrations or EVSE installations in most regions (including in 46 U.S. states) (Baumhefner et al., 2016). The United Kingdom, however, requires notification of one's local distribution network operator in order to claim rebates for EVSE installations. The program is implemented through authorized charge point installers in order to simplify the process for customers (OLEV, 2016).

Governments may investigate policies to notify utilities of such developments without compromising privacy to increase the feasibility of utility engagement with electric vehicles. Potential sources of information include car dealerships, auto registration agencies, and electricians. California plans to use the revenue generated from the sale of Low-Carbon Fuel Standard credits (discussed later in this report) to fund incentives that enable notification (CPUC, 2014a; 2014b).

Carbon reduction and renewable energy regulations. A number of governments have created clean energy and greenhouse gas reduction regulations in many forms, which will significantly shape the development of electricity sectors over the coming decades. In the United States, 29 states and the District of Columbia have adopted Renewable Portfolio Standards that mandate a percentage of electricity come from renewable sources by a given year, and eight other states have non-binding targets (DSIRE, 2016). The U.S. federal government also adopted the Clean Power Plan to restrict greenhouse gas emissions from power plants, although the plan faces legal challenges and an uncertain future amid the U.S. political transition (U.S. EPA, 2016). In Europe, the European Union and other countries have created a cap-and-trade system to limit CO_2 and local pollutants from power plants, factories, and airlines, in addition to stringent renewable energy and CO_2 targets for each country (European Commission, 2016a; 2016b). Some countries, such as the United Kingdom, have their own more ambitious standards. The Regional Greenhouse Gas Initiative (RGGI), a cap-and-trade program for power plants in nine northeastern U.S. states, has allowed these jurisdictions to reduce power-sector CO_2 pollution by more than 45% since 2005 (RGGI, 2016). California and Québec also operate a cap-and-trade scheme, which generates revenue for environmental programs in those jurisdictions (ARB, 2013). British Columbia has a provincial carbon tax; a similar tax is scheduled to go into effect in Chile in 2018 (Ministry of Finance, 2016; Benavides et al., 2015).

These various policies all have the goal of driving down emissions from the power sector, which will, in turn, maximize the environmental benefits of electric vehicles. Greater renewable generation will require more flexibility in the grid, making smart charging of electric vehicles especially promising as an energy storage technique. This also presents an opportunity to generate hydrogen with excess renewable energy during periods of high supply and low demand, which could be used to fuel hydrogen vehicles (discussed further in Section V). Policies to reduce power sector emissions, whether through renewable portfolio standards, cap and trade programs, or carbon taxes, reduce the life-cycle emissions of ZEVs and could accelerate decarbonization of the transportation sector.

EVSE SUBSIDIES

Home charging. In North America, electric vehicles are typically sold with a Level 1 (120 V) charging cable included, which can plug into a standard 120V outlet and requires up to 12 hours to charge. Level 2 chargers offer greater convenience to electric vehicle owners and potential grid benefits to utilities, but can be expensive, averaging about $1,500 to purchase and install (DriveClean, 2016). To obtain these benefits, utilities can help defray drivers' initial installation costs. Examples of utilities doing this include Puget Sound Energy in Washington, which offers a $500 rebate on residential Level 2 chargers in exchange for monitoring charging data (RAP, 2015a), and Austin Energy in Texas, which will pay for half of the purchase and installation costs of a Level 2 charger for customers who agree to be placed on time-of-use rates (Austin Energy, 2015).

The need for such programs is less clear in Europe and in other parts of the world where 240V chargers are included with most electric vehicle purchases. However, utilities could consider subsidizing more advanced smart-charging EVSE or higher-power charging stations that use 400 V connections in order to realize grid benefits. A study from Silver Spring Networks estimates that providing a $1,000 home EVSE subsidy in exchange for basic demand response participation provides grid benefits 2.7 times greater than the costs, though this ratio drops to 1.4 if the utility must also provide a new meter (Silver Spring Networks, 2013). Additionally, utilities in all regions could play an important role in adding EVSE to serve drivers living in multi-unit residences, which represent a major gap in current charging infrastructure (Baumhefner et al., 2016; van 't Hull & Linnenkamp, 2015).

Commercial and workplace charging stations. As of 2016, workplace and commercial charging makes up a small fraction of all charging in most regions, but access to workplace charging may be critical for electric vehicle adoption: a U.S. Department of Energy (U.S. DOE) survey found that prospective electric vehicle consumers are 20 times more likely to buy an electric vehicle if they have access to charging stations at work (Rushlow et al., 2015). Widespread workplace and commercial charging could also help utilities to manage mid-day peaks and match electric vehicle charging to solar energy.

Utility subsidies could appeal to business owners who are interested in providing workplace charging but may be deterred by the high upfront cost. The Los Angeles Department of Water and Power, for example, offers rebates up to $1,000 for commercial Level 2 charging stations (typically covering the full cost of the EVSE) and will subsidize more expensive DC fast charging stations (up to $15,000) at sites with enough visitors (Salisbury & Toor, 2015). Other programs subsidize a certain percentage of EVSE cost; for example, Southern California Edison's Charge Ready program pays 100% of the cost for chargers in multi-unit residences and in disadvantaged communities, but only 50% for chargers at workplaces (CPUC, 2016a). This approach may help to guide investment towards locations where chargers would be well-utilized and allow property owners a greater sense of ownership.

Power companies in Europe have frequently built charge points in office parks and parking garages, and some utilities, such as UK Power Networks, have provided EVSE to employers as part of limited trials (Auendi et al., 2014). However, utility partnerships with local businesses in Europe are less common than in the United States. Subsidy programs could allow power companies to increase long-term revenue and useful data on consumer charging behavior.

UTILITY-OWNED EVSE

For utilities hoping to support electric vehicles, providing charging stations may be seen as a natural step. Utilities have access to the power distribution infrastructure needed to accommodate EVSE, and they could benefit from high returns on their capital expenditures, eventually helping to lower rates for all ratepayers. With unique expertise in the electrical system and the ability to offset costs through electricity sales, utilities can be critical in fulfilling government plans to build out charging station networks, especially in the early stages of EVSE deployment (E3, 2014a).

Home and workplace EVSE. Utilities could consider providing utility-owned infrastructure to residents and businesses to reduce costs for consumers while enabling electric vehicles to provide grid benefits through load scheduling and smart charging. This would allow utilities to choose the infrastructure that best fits their interests—for example, smart-charging EVSE with approved metering technology—and would make it much easier for utilities to coordinate behind-the-meter resources. According to one model, these benefits far exceed the costs of providing and installing the EVSE (Silver Spring Networks, 2013).

Forty-two utilities have signed on to the U.S. DOE’s Workplace Charging Initiative to provide charging infrastructure at their own facilities, and many also have created programs to install workplace EVSE at other locations in their regions (U.S. DOE, 2015). A few utilities, such as Avista in Washington and Pepco in Maryland, have distributed charging infrastructure to residents and workplaces as part of trials (Nedler et al., 2016; Gonzalez, 2014). No utilities currently have large-scale programs for owning home or workplace charging.

Public EVSE networks. The role of utilities in providing public charging infrastructure varies widely around the world and is the subject of great debate. In Europe, large energy companies have been responsible for a significant fraction of all public charging stations—for example, energy supplier RWE owns more than 2,800 charging stations across Germany and other countries, and its competitors Vattenfall, E.ON, and EnBW also operate substantial networks, making up over 35% of all public charging stations in Germany (Funke et al., 2015). In the Netherlands, Norway, and Denmark, utilities have collaborated to open nationwide networks through the groups EVnetNL, Grønn Kontakt, and Clever, respectively (van Deventer et al., 2015; Clever in Sweden, 2016; Grønn Kontakt, 2016). Large generation or transmission companies have been most proactive in building EVSE, but local municipal utilities have also launched their own projects in some countries, such as BKK in Bergen, Norway, which recently opened the largest fast-charging station in Europe (ABB, 2015). In other countries, such as the United Kingdom and Germany, distribution network operators are not allowed to own or operate behind-the-meter infrastructure such as EVSE or storage, although there are efforts to revise these rules in response to a changing electrical system (Ofgem, 2015; Verbruggen, 2016).

A similar situation exists in China, where the state-owned transmission and distribution operators have led the way in deploying charging infrastructure in the country. State Grid Corporation of China and China Southern Power Grid have together opened more than 27,000 charging stations across the country, as well as more than 800 electric vehicle battery-swapping stations for buses and select models of cars (State Grid Corp., 2013). Further expansion with heavy support from the central government is planned, with a goal of 120,000 stations by 2020, although private competition is increasing (Chang, 2016).

In North America, utility investment in public electric vehicle charging networks is still in its early phases, but shows signs of growing quickly. Several municipal utilities, including Austin Energy and Kansas City Power and Light, have deployed charging stations across their respective service areas in efforts to make their cities friendlier for electric vehicles (Austin Energy, 2015; KCP&L, 2016). Larger investor-owned-utilities (IOUs) in the U.S. have generally not created programs to invest in charging infrastructure, but Southern California Edison, San Diego Gas & Electric, and Pacific Gas & Electric have received approval to deploy public charging networks spanning across multiple cities in California, as are Commonwealth Edison in Illinois and Green Mountain Power in Vermont (CPUC, 2016a; 2016b; 2016e; Salisbury & Toor, 2015; Green Mountain Power, 2016). In Canada, Hydro Québec operates an extensive network of DC fast chargers, called the Electric Circuit, across Québec and Ontario (Hydro Québec, 2016).

RATE STRUCTURES

By offering and promoting appropriate rate structures to customers, utilities can encourage the shifting of electric vehicle charging loads to off-peak hours, minimizing grid impacts and reducing costs for electric vehicle owners. Utilities around the world have already successfully adopted electric vehicle-friendly rates, and research is ongoing on more advanced programs.

Time-of-use electric vehicle charging rates. A simple, but effective step for utilities is to implement time-of-use (TOU) rates, in which electricity prices vary over predetermined periods of the day. Typically, there are two or three rate tiers during a day, with prices also sometimes varying by season or on weekends. Naturally, costs are higher (often by a factor of two or more) during peak demand times, but total average prices are typically designed to be revenue-neutral and reflect the marginal cost of electricity generation. The technical barriers to implementing TOU rates are relatively small: they require smart meters such as those already installed in many parts of the world, or utility-approved metering equipment integrate into the electric vehicle or EVSE. Electric vehicle owners can take advantage of TOU rates with minimal effort by using a simple charging timer (included on almost all electric vehicle models and in many home charging stations).

TOU rates have proven to be very effective at delaying electric vehicle charging until off-peak hours, as demonstrated by numerous utility trials—in San Diego, for example, electric vehicle drivers completed more than 80% of their home charging during their “super-off-peak” period between midnight and 5 a.m. (Cook et al., 2014). Trials of TOU rates for electric vehicle owners by Baltimore Gas and Electric and Pepco in Maryland were also successful and have also led to permanent new rate offerings (PSC, 2015). Customers can realize significant savings from TOU rates: estimates from across the United States range from $200 to $450 in annual savings (Berkheimer, 2015; Salisbury &

Toor, 2015). These rates have been implemented successfully (for electric vehicle owners and others) by utilities in the United States, Germany, the United Kingdom, Japan, and other regions, although the long-term durability of such programs for mainstream adopters will be determined in the coming years.

While TOU rates work very well at low levels of electric vehicle uptake, there is concern that this structure could create a new peak at the beginning of the off-peak period as many electric vehicles begin charging simultaneously (Fitzgerald, 2016). One possible solution lies in deploying controllers that schedule when charging is to be completed rather than when it begins, thereby staggering when charging begins and reducing the sudden grid impacts. However, this capability is not yet universally available.

Dynamic rates. An extension of TOU rates, dynamic, or real-time, electricity pricing would allow utilities to adjust rates even more frequently to reflect wholesale market prices, grid capacity, or renewable energy availability. Dynamic prices would help to reduce secondary peaks from TOU rates and match electric vehicle charging to solar or wind resources that otherwise might have to be curtailed (CPUC, 2016b). Though these rates could increase savings for electric vehicle drivers, they could also face skepticism from consumers (Fitzgerald, 2016). This opens opportunities for electric vehicle service providers and aggregators to navigate dynamic prices and present clear charging schemes for users, thereby minimizing confusion while still allowing the grid benefits of dynamic rates.

Dynamic rates are still relatively untested, although there are trials underway by Nord-Trøndelag Elektrisitetsverk Nett in Norway and San Diego Gas & Electric in California, with prices posted one day ahead in the latter trial (Davis, 2014; CPUC, 2016b). Such a scheme has thus far induced the development of EVSE-embedded meters and increased communication between the utility, the EVSE, and the electric vehicle. While more research is required, dynamic pricing represents a promising option for passively managing electric vehicle charging to reduce grid impacts and maximize customer savings.

Discouraged rate structures. In contrast to TOU and dynamic tariffs, other rate structures can discourage electric vehicle ownership and increase electricity costs. Inclining block pricing, where customers' rates per kWh increase after certain levels of consumption are reached each month, are helpful for encouraging energy efficiency. However, this program could cost electric vehicle owners who would be pushed into a higher tier—one estimate from Xcel Energy in Colorado puts the additional cost at $46 per year (Xcel Energy, 2016).

Likewise, demand charges add a fee for a customer's maximum power usage (in kW) within a given billing period to account for the distribution infrastructure required to serve that customer. These are commonly charged by DSOs throughout Europe (particularly in the United Kingdom) and are sometimes also charged to commercial customers in the United States (Eurelectric, 2013). This has the effect of reducing the value of electrification for electric vehicle owners and could discourage installation of higher-power EVSE or multiple charge points at a business (NAS, 2015). However, some utility regulators are concerned about the implication of cost shifts from waiving demand charges for customers (CPUC, 2016c).

If utilities find tiered or demand rates effective for traditional customers, they can also solve this problem by installing a separate meter for the EVSE (or utilizing an approved, embedded meter within the electric vehicle or EVSE). This would allow the utility to offer a TOU or dynamic rate for vehicle charging while using a flat, tiered, or demand-based rate plan for the remainder of the site's energy usage. For example, SDG&E's electric vehicle rate has only per-kWh charges (CPUC, 2016b). This can promote grid-friendly, cost-saving electric vehicle charging practices while encouraging household energy efficiency and minimizing inconvenience to customers, and is therefore frequently preferred by utilities and electric vehicle owners alike. This also makes it possible for utilities to implement discounted rates as a way to encourage adoption of electric vehicles, such as that offered by Los Angeles Department of Water and Power (AFDC, 2014).

Alternatively, utilities can request temporary waivers for high-power-charging customers such as transit agencies and DCFC operators, whose business cases can be challenged particularly during initial phases when a high-power charger has limited utilization over which to spread fixed costs. However, upon further use, scheduling loads with charging management systems can reduce the cost impact from demand charges (CARB, 2016b). Furthermore, research is being completed to analyze the benefits of considering high-powered EV charging among other demand-side management technologies (ESNA, 2016).

Green power mix options. A number of utilities and electricity retailers around the world offer special power plans that sell electricity certified as "green," or coming from renewable sources, at an additional cost. By opting for these special tariffs, customers can reduce their own carbon footprint and support the development of renewable energy in their region, and use of green power plans for electric vehicle charging would also lead to completely emissions-free driving. In North America, green power options are offered by many major utilities including Pacific Gas & Electric in California and Con Edison in New York, and twelve states offer competitive markets to buy green power (U.S. DOE, 2016). In Europe, there are a wide variety of green tariff options available in most countries, although regulations regarding the labeling and certification of these tariffs are still evolving (Mühlenhoff, 2016). Several retailers dedicated specifically to guaranteeing green power have also emerged, such as Bullfrog Power in Canada or Lichtblick in Germany. Combining green power plans and electric vehicle-friendly rate structures would support true decarbonization of the power grid and could boost demand for renewable energy.

SMART CHARGING

Although indirect charge management strategies, such as TOU rates, allow utilities to access some grid benefits, successful vehicle-grid integration will ultimately require smart charging technology. Smart charging refers to any program that manages electric vehicle charging to promote grid stability or more efficient resource usage, and can take on a variety of forms, including demand response, one-way controlled charging, or vehicle-to-grid. Utilities and research organizations around the world are actively exploring smart charging technologies and their capabilities in order to maximize the benefits to electricity providers and electric vehicles owners. Many of the trials conducted thus far have been conducted in fleet settings, as fleets with set duty cycles may be able to benefit from smart charging programs without sacrificing flexibility during their normal operational times.

Table 2 displays a number of smart charging trial projects and their unique characteristics. The number of vehicles involved, the location of charging, and the type of smart charging capabilities involved vary, indicating a number of models that may be useful in further developing this technology. As the benefits of smart charging become more widely publicized and utilities' interest in electric vehicles grows, trial projects have grown in size and scope.

Table 2. Examples of smart charging trials

Region	Electricity sector partner	Number of stations	Setting	Services offered	Status
Delaware	PJM	15	University	V2G (paid)	In progress from 2011
Victoria, Australia	United Energy	10	Residential	DR, V1G	Completed 2013
London, United Kingdom	UK Power Networks	47	Street	DR	Completed 2014
San Diego, California	San Diego Gas & Electric	150	Fleet	V1G, DR	Completed 2015
United Kingdom	Scottish & Southern, Northern Powergrid	100	Residential	DR, frequency response	Completed 2015
Maryland	Pepco	200	Residential	DR, delayed charging	Completed 2016
Berlin, Germany	LichtBlick	40	Fleet	V2G, renewable integration	Completed 2016
San Francisco Bay Area, California	Pacific Gas & Electric	100	Residential	DR, modulated charging, battery second life	In Progress from 2015
Utrecht, Netherlands	Stedin, ElaadNL	1000	Street	Renewable integration, V2G	Beginning 2016

DR = demand response (on/off control); V1G = fully controlled one-way charging; V2G = vehicle-to-grid (two-way) smart charging

Demand response. The simplest smart-charging programs involve DR, which means pausing charging at times of peak demand or when supply is disrupted. This not only prevents drops in grid voltage or frequency, but also minimizes the number of expensive and inefficient "peaker" power plants that need to be activated, creating cost savings that can be passed on to consumers (Baumhefner et al., 2016).

Because most charging takes place in residential settings, several utilities have sought to integrate DR into normal home charging. This includes the My Electric Avenue project in the United Kingdom, which linked clusters of electric vehicles across the country and used the Esprit software program to pause charging in some vehicles when distribution circuits were at risk of overloading. The project estimates that the program could save more than 2.2 million pounds by 2050 (EA Technology, 2016). In the United States, Pepco recently completed a similar project with 200 households in Maryland in a unique effort that focused on reducing metering and infrastructure costs for consumers (St. John, 2014).

Demand response can also be programmed into public charging infrastructure, allowing this strategy to be paired with utility-owned EVSE networks. This has been implemented at 47 stations in London as part of the Low Carbon London project, with estimated savings of $70 million over the next eight years (Auendi et al., 2014). Southern California

Edison also incorporated demand response into a workplace charging pilot it operated, with lower rates for customers who allowed their charging to slow or stop when demand increases (CPUC, 2013a). DR-capable EVSE is close to widespread deployment—in California, DR technology is now required for new public Level 2 EVSE in preparation for widespread implementation (CPUC 2016b).

Controlled charging. More complex smart-charging programs allow not only pausing of charging, but also scheduling of charging and modulation of charging power to meet the needs of the user and the grid. This allows utilities to precisely fit electric vehicle charging into times when the grid has the most spare capacity and, in the best case, avoiding the need to upgrade distribution infrastructure or build more generation capacity. There are still technical hurdles to this technology: Most charging stations cannot vary charging current, and there are few standardized protocols for EVSE-grid communication, although efforts to create standardized interfaces are in progress, such as ElaadNL's work on the Open Smart Charging Protocol (Montes Portela et al., 2015).

Numerous studies have analyzed the potential for controlled charging to alleviate grid congestion concerns, with very convincing results. The Sacramento Municipal Utility District estimates that one-way smart charging will reduce grid upgrade expense by over 70%, and the Green eMotion project found that when using smart charging, network reinforcement costs in the European Union dropped by 50% while also reducing greenhouse gas emissions (Berkheimer et al., 2014; Green eMotion, 2015). As suggested by these studies and others, most ancillary services (described in Section II) could be provided with this form of smart charging without causing any additional stress on batteries or requiring additional hardware in the vehicle. As these programs approach commercialization, different actors within the electricity system must collaborate to optimize the economic and environmental benefits of charge scheduling while also ensuring that drivers can meet their mobility needs—this may require aggregators to manage the software and communication for such transactions.

Vehicle-to-grid. The most advanced and valuable form of smart charging is vehicle-to-grid (V2G), or two-way charging. As described in Section III, V2G allows electric vehicle batteries to discharge power back into the grid when needed, making the batteries an energy storage resource in addition to a mobility device. With full V2G capabilities, electric vehicles could be charged when power is cheapest and most abundant and fed back to the grid when the power is most valuable, providing financial benefits to consumers. In most scenarios, a group of electric vehicles would be linked together to send power into the grid, forming a "virtual power plant."

Table 3 shows the estimated value of grid services from electric vehicles in various markets. Although the value of V2G services is uncertain and varies by region, some estimates suggest that electric vehicles could generate significant amounts of money. A number of U.S. and Europe-based studies and real-world trials indicate that electric vehicles could provide grid services with value ranging from around $100 for simple DR to thousands of dollars annually for V2G. The specific value is heavily dependent on the charging speed and amount of battery storage available, and also varies by region, largely due to differences in electricity prices and power generation mix. These savings stem primarily from reduced generation costs and reduced need for distribution system upgrades, and can be passed on to the electric vehicle owner to substantially reduce the cost of ownership. The values obtained in Table 3 may not reflect typical operating patterns of a private passenger vehicle and could be lower at higher uptake levels.

Table 3. Estimations of the per-vehicle value of grid services from electric vehicles

Service offered	Region	Estimated Annual Value	Source
DR	California	Up to $1,026	BMW USA, 2016
V2G regulation	U.S. Mid-Atlantic	$1,800	Markel et al., 2015
V2G regulation	California	$2,520	Gorguinpour, 2013
DR, V2G regulation (3.3 kW)	Washington	$750	Markel et al., 2015
V2G regulation, 1.3 kW	New York	$277-$837	White & Zhang, 2011
V2G regulation, 10 kW	New York	$2,200-$2,500	White & Zhang, 2011
DR	New York	$78	MJ Bradley, 2015
V2G regulation (SRL)	Germany	$976	Schuller & Rieger, 2013
V2G regulation, 3.7 kW	Germany	$550	Raths et al., 2013
V2G regulation (SRL)	Germany	$610-$785	Arnold et al., 2015
DR, load shifting	Spain	$163	Madina et al., 2016
V1G regulation	Spain	$280	Madina et al., 2016
CA LCFS credit sales	California	$297	CARB, 2016c

Based on trial **Based on model**

DR = demand response (on/off control); V1G = fully-controlled one-way charging; V2G = vehicle-to-grid (two-way) smart charging; SRL = secondary reserves; kW = kilowatt; LCFS = Low Carbon Fuel Standard LCFS credit sales calculated assuming a 2016 Nissan Leaf with average U.S. driving habits, charged with electricity from the California power grid. The values shown in the third row reflect modeled values for a real trial project at the Los Angeles Air Force Base in California—final values are not publicly available.

Despite this significant value, V2G faces much greater obstacles and costs than DR or one-way controlled charging do. Currently, no electric vehicles in mass production support bidirectional charging, and these features would require expensive additions to the vehicle's electronics, raising questions about the technology's cost-effectiveness. Charging stations and meters (either in the vehicle or at the building level) would also have to be substantially modified. There are also concerns about the effects of V2G charging on battery life, although several studies show that well-managed two-way charging would cause minimal battery damage and can actually *reduce* battery degradation compared with typical charging practices, by lowering the average state-of-charge (Wang et al., 2016; Putrus et al., 2015). In addition to these technical challenges, there are questions about consumer willingness to sacrifice flexibility—however, one study has found that 95% of vehicle-to-grid charging requirements could be accomplished without any disruption to driver needs (Saxena et al., 2015). In other applications, such as fleets or buses, it may be even easier to use vehicles for grid services based on their predictable schedules.

A number of utilities are working on research and demonstrations of V2G technologies, including the compensation of electric vehicle owners. A project at the University of Delaware in partnership with NRG Energy and BMW has been especially influential as the first example of electric vehicles receiving payment for V2G grid services. In this pilot project, 15 modified BMW i3 vehicles have been aggregated to feed energy into the PJM grid for frequency regulation during peak demand periods, each vehicle receiving up to $1,800 annually (Markel et al., 2015). The U.S. Department of Defense has also investigated incorporating V2G charging in its electric vehicle fleets at several military bases in the United States; the largest trial is in progress at the Los Angeles Air

Force Base, with utility Southern California Edison helping to manage grid integration and solve technical challenges (CPUC, 2013b). The INEES project in Germany built 40 V2G-capable Volkswagen vehicles, whose owners were compensated for stabilizing the grid while experiencing minimal inconvenience (Arnold et al., 2016). These projects and others are crucial for informing the development of technologies and policies to push V2G to mainstream markets. In California, several state agencies and CAISO developed a roadmap for purposes of commercializing vehicle-grid integration technologies (CAISO, 2014).

UTILITY PARTNERSHIPS

As discussed above, transportation electrification has the potential to benefit electric utilities in a number of ways. However, VGI projects may also present benefits to other businesses and to society as a whole. For that reason, utilities may be able to best take on the challenges of vehicle-grid integration through collaboration with other stakeholders. Such partnerships can give utilities valuable insights into new technologies and lead to new business models in this rapidly expanding field, as well as defray the costs (in money and time) of innovative new programs.

A number of utilities have already created partnerships and identified areas for collaboration to study and promote electric vehicles. Table 4 highlights a few existing partnerships to date. As shown, existing utility partnerships include automakers, EVSE hardware and software providers, IT and software companies, research organizations (including universities and other institutions such as the Electric Power Research Institute, or EPRI, and the Fraunhofer Institute), and governments at different levels. Naturally, some projects may be shared between more than two stakeholders, and every partnership would be uniquely suited to focus on specific applications.

Table 4. Examples of opportunities for utility collaboration with other electric vehicle stakeholders and exemplary partnerships already completed or underway

Potential partners	Areas for cooperation	Examples
Automakers	Smart charging, BSL, aggregation, standards	• BMW and PG&E i ChargeForward • ElaadNL with Renault in Netherlands • ROEV charging network project
Charging infrastructure providers	Connectivity, DR, V2G, open standards	• Siemens and Duke Energy VersiCharge • EVSE LLC and SCE workplace charging
IT/software companies	Charge optimization, security, aggregation	• HECO and Greenlots Battery-DCFC • My Electric Avenue
Academia and research organizations	Local modeling, pricing	• PJM and Univ. of Delaware V2G • eConnect Germany project • Energy Technology Institute and EDF Energy CVEI
Local and state government	EVSE deployment, local modeling, outreach	• San Diego readiness study • Plug In BC (BC Hydro)
Federal government	Standards, R&D	• U.S. Dept. of Energy SGIG • U.S. Dept. of Energy–Edison Electric Institute MOU • Ofgem Electricity Network Innovation Allowance

Partnerships between utilities. Some projects, such as deploying electric vehicle charging networks or creating smart charging standards, may require collaboration across jurisdictions and among multiple utilities. Though this may seem to hurt competitiveness between utilities (and could further stifle private-sector charging infrastructure), collaborative programs could substantially boost the electric vehicle market, leading to greater future growth. Perhaps the most successful example of such a partnership is the Elaad Foundation, a partnership of the eight largest DSOs in the Netherlands. The group manages more than 3,000 public charging stations, maintains an international standard for public charge station interoperability, and continues to research smart charging technologies (ElaadNL, 2016). Other regions have also adopted this model: Clever, a group owned by five utilities in Denmark, is the largest operator of EVSE in that country and has now expanded into Sweden, while 23 utilities in Norway have together opened a nationwide network of DC fast chargers under the Grønn Kontakt brand (Clever in Sweden, 2016; Grønn Kontakt, 2016).

ADDITIONAL NOTEWORTHY PROGRAMS

While the previously discussed topics encompass many utility best practices related to electric vehicles, some utilities have explored other unique programs and technologies. While these are generally more innovative programs that are not yet practical for widespread deployment, they may lead to further innovation and increase the value of electric vehicles in the future.

Battery second life. Despite the potential for BSL programs to provide significant storage capacity to the grid, few companies have tested the technology, possibly because most electric vehicles are still too new to be put out of service or even need new batteries. However, a few projects seek to prove the viability of this model and work through technical issues. For example, BMW has partnered with Swedish power company Vattenfall to build a 2 MWh battery second life system designed to compensate for renewable energy fluctuations in Germany (Colthorpe, 2015). In California, BMW is also using used batteries to fulfill power requirements for demand response capacity that not met directly by the fleet of i3 electric vehicles for Pacific Gas & Electric as part of the i ChargeForward project. Other automakers have expressed interest in reusing electric vehicle batteries to reduce the vehicles' total lifecycle cost and environmental footprint—Nissan has announced multiple commercial battery second life storage operations and Daimler is building a 13 MWh project in Germany (Nissan, 2015; Daimler AG, 2015).

Storage and charging combinations. As previously noted, high concentrations of simultaneously charging electric vehicles could put strain on the distribution grid and cause frequency fluctuations, especially at high charging power rates. One possible solution is to pair electric vehicle charging stations with stationary energy storage, which would allow utilities to flatten the electrical load and potentially increase renewable energy usage.

A few demonstration projects in North America and Europe have explored this idea. Hawaii Electric Company has partnered with Greenlots to build DC fast charging stations with large battery storage to avoid upgrades in the distribution system and make use of Hawaii's substantial solar resources (HECO, 2016). In the United Kingdom, this idea has been paired with battery second life through the EVEREST system, which uses a large bank of used batteries to charge electric vehicles and return energy to the grid to provide balancing services (Akers et al., 2015). The SMART charging stations in the U.S. state of Tennessee, built by the Tennessee Valley Authority, include an on-site solar panel with batteries that supply 65% of electric vehicle charging power to minimize grid impacts and feed energy back to the grid when available (Halliwell, 2011). The Energy OASIS project, developed by the British Columbia Institute of Technology, Natural Resources Canada, and BC Hydro in Burnaby, British Columbia, combines a large solar array, battery storage, and fast charging stations in order to allow fast charging with no impact to the electric grid (Natural Resources Canada, 2016b).

Credits under California's Low Carbon Fuel Standard. The Low Carbon Fuel Standard program in California was created in 2007 with the goal of reducing the average carbon intensity of fuels in California by 10% by 2020 (CARB, 2016a). The program uses a credit-trading scheme, and because power used for electric vehicles produces far less CO_2 per distance traveled than traditional fuels, utilities are able to collect credits as fuel providers and sell them to fuel producers (INL, 2015). For regulated power companies, this revenue would be passed on to electric vehicle owners, providing direct compensation for the environmental benefits of their transportation choices. In California, the Public Utilities Commission found that the sale of credits was necessary to fulfill the utilities' obligations to reduce the social cost of energy services (CPUC 2014a). In addition, CPUC determined that upfront rebates or annual rebates were most effective ways to use LCFS revenue to increase electric vehicle adoption (CPUC, 2014b). PG&E has created a new upfront rebate program worth $500 for electric vehicle owners in their territory (PG&E, 2017). More broadly, an estimate of credit revenue from the California Air Resources Board suggests a value of about $297 available to every electric vehicle owner annually (CARB, 2016c). Similar programs, whether through a market or with state incentives, could help promote electric vehicle uptake and reduce emissions.

Advanced electric vehicle R&D at utility laboratories. Electric vehicle technology is evolving quickly, and utilities can guide the future of the technology directly through laboratory research and development projects. The best examples of utility research on electric vehicle technologies are found in Canada: Hydro Québec and BC Hydro operate lab research companies, called IREQ and Powertech, respectively. IREQ has been an influential player in battery technology for many years, and has even established a subsidiary company, TM4, to produce electric powertrains. Powertech Labs carries out extensive VGI research and also builds hydrogen fueling and storage infrastructure.

EVSE deployment as emissions mitigation. While some utilities have built electric vehicle charging networks to diversify their business and explore future smart charging applications, others could support electric vehicles and provide charging stations as a way to mitigate pollution and greenhouse gas emissions from other activities. In at least one case, a utility has provided charging stations and support of electric vehicles as an explicit compensation for violating pollution standards: Duke Energy has agreed to build 200 charge points at 50 sites in North Carolina as part of a settlement for excess SO_x emissions at coal-fired power plants (Wheeless, 2016). While it is preferable for utilities to invest in electric vehicles of their own volition, adding options such as this to regulations in other areas could help to spur utility support of electric vehicles in regions where power companies would otherwise be reluctant to engage in the sector.

NOTABLE EMERGING PROGRAMS

There are several projects underway in 2017 that represent significant advancement in utility support of electric vehicles, and their outcomes may influence future investment and other utility programs. To help give a sense of the global developments underway among utilities, we highlight five major electric vehicle developments in California, the Netherlands, the United Kingdom, British Columbia, and across Europe, which may eventually be seen as best practices as results become available.

In California, Southern California Edison (SCE), San Diego Gas & Electric (SDG&E), and Pacific Gas & Electric (PG&E) are developing large electric vehicles charging networks, the first to be operated by investor-owned utilities in the United States (see CPUC, 2016d). This charging build-out strategy is designed to be mutually beneficial for utilities' long-term planning, electric vehicle users, and other ratepayers. The three programs follow different approaches for the ownership and management of charging stations: SDG&E will build, own, and operate all stations in order to test a number of rates and demand response programs; PG&E will install and own the make-ready infrastructure and a select number of stations in disadvantaged communities while providing rebates for additional independently-owned stations; and SCE's stations will be installed by the utility but owned and operated by site hosts (CPUC, 2016e; Fitzgerald et al., 2016). In addition, all three of these programs will include substantial consumer awareness campaigns to increase utilization of the utilities' transportation electrification programs and educate consumers about the benefits of electric vehicles (CPUC, 2016a; 2016b; 2016c; 2016e). Utilities across the United States, as well as public utility commissions that regulate utilities, are watching these programs closely and considering adopting similar policies.

ElaadNL, working with Renault and the city of Utrecht in the Netherlands, is building 1,000 public solar-powered smart charging stations with battery storage around the Utrecht region in the largest smart charging demonstration to date. Renault is launching a car-sharing service of electric vehicles to test the stations, which will eventually be upgraded with V2G capabilities (van Kaathoven et al., 2016). This project continues ElaadNL's extensive work on EVSE software and standards, including updating OCPP to manage local loads and link with renewable sources.

On the heels of the My Electric Avenue project (discussed previously), the distribution network operator Western Power Distribution is beginning Electric Nation, a new smart-charging demonstration project in several regions of the United Kingdom. The project will install up to 700 residential electric vehicle smart chargers, enabling V1G charging in order to study the potential benefits to the electric grid (CarConnect, 2016). It also includes new consumer-facing technology, such as an app to control charging preferences. The project is the largest to use such advanced technology, and its results could be important in guiding other utility smart charging and consumer engagement programs. The My Electric Avenue project also led to the creation in 2016 of the Low Carbon Vehicle Partnership's EV Network Group, which will work to foster collaboration between different government and industry stakeholders on issues relating to electric vehicles' network impacts (LowCVP, 2016).

BC Hydro is continuing expansion of its Electric Vehicle Smart Infrastructure program, including deploying DC fast charging (DCFC) stations along critical corridors across the province of British Columbia. Additionally, the utility is adding smart charging programs at "signature sites" to complement its comprehensive evCloud EVSE data aggregation platform (Natural Resources Canada, 2016a). This represents one of the largest utility-owned DCFC projects to date and could help to develop best practices for high-speed charging.

Multiple groups in Europe are working to realize international EVSE interoperability, popularly known as "e-roaming." Ladenetz, a collaboration between three municipal utilities in Germany and several universities, operates the e-clearing.net platform using the Open Clearing House Protocol (OCHP) and allows e-roaming across all or part of ten European countries (Bakker & Trip, 2015). The European Commission's Green eMotion project also seeks to create harmonized standards for e-roaming across Europe, with help from many utilities and industry partners (Green eMotion, 2015).

V. UTILITY SUPPORT OF HYDROGEN

In addition to the many programs supporting plug-in electric vehicles, some power companies have also shown interest in supporting the growth of hydrogen fuel cell vehicles, creating programs that could accelerate the development of hydrogen as a fuel source. While activity in this area is somewhat more limited, there are opportunities for utilities as hydrogen suppliers and distributors to power the hydrogen economy and fuel cell vehicles of the future.

POWER TO GAS

In regions where solar and wind energy are abundant, some utilities have faced issues with an oversupply of renewable energy at certain times of the day, forcing clean resources to be curtailed. This situation is likely to become more prevalent as countries increase their renewable energy supply to reduce greenhouse gas emissions. One potential way to store this energy is to generate hydrogen through electrolysis, a process known as power to gas (P2G).

P2G technologies face several challenges, including high initial cost, low efficiencies, and low demand for hydrogen, but with ongoing research on electrolysis catalysts and increasing demand for hydrogen, the technology's feasibility is likely to increase (Bünger et al., 2014). Hydrogen electrolysis can be widely distributed (although electrolyzer efficiency increases with scale), can use reclaimed water, and creates no emissions (California Hydrogen Business Council, 2015). Hydrogen generated through P2G has a variety of potential uses, including power generation with fuel cells, which could provide ancillary services; direct injection into the natural gas grid for use in heating or generation with modified turbines; sales to industry for manufacturing of other chemicals; and of course, use in hydrogen fuel cell vehicles. This technology is quickly gaining in popularity, and could allow utilities to support hydrogen vehicles by greatly increasing the supply of fuel.

Utility P2G demonstration projects. Utilities in Germany, the Netherlands, California, and elsewhere have built power to gas demonstration projects to investigate the potential to accommodate an oversupply of renewable resources. Utilities in Germany have been at the forefront of P2G research—for example, 12 municipal utilities in the Thüga Group have partnered to build and operate a large electrolysis station in Frankfurt to utilize extra wind and solar power (Thüga AG, 2012). Major power companies RWE, EnBW, and E.ON also operate P2G facilities (Bünger et al., 2014). Most utility P2G facilities today, in Germany as well as in other countries, inject their hydrogen into the natural gas grid; natural gas-burning systems can theoretically tolerate up to 20% hydrogen content, and some gas grids today already contain up to 10% hydrogen (California Hydrogen Business Council, 2015).

HYDROGEN DISTRIBUTION AND FUELING STATIONS

Future growth in the fuel cell vehicle market would require a large network of hydrogen fueling stations, and utilities could play a role in building and operating this network. Many utilities have experience operating gas distribution infrastructure, and fueling stations could be paired directly with P2G or electrolysis stations to take advantage of utilities' other assets. Furthermore, as with electric vehicle charging networks, utilities may rate-base these investments (where regulations allow) in order to reduce the upfront costs of this new technology. Still, regulations covering hydrogen as a transportation and utility fuel are evolving, and there have been claims that utility ownership of hydrogen fuel stations is anticompetitive.

As of 2016, few utilities have invested in public hydrogen filling stations. This is likely due to low demand for hydrogen in the transportation sector, poor commercial performance of early refueling stations, and government programs that have prioritized electric charging networks (or built hydrogen networks without utility involvement). One notable exception is the HafenCity hydrogen fueling station in Hamburg, built by Vattenfall to supply Hamburg's fuel cell buses as well as passenger cars (Lutz, 2012). As the largest hydrogen filling station in Europe by daily capacity, this project represents a model for future utility ownership of hydrogen filling stations. In the United Kingdom, Scottish and Southern Energy contributed to the development and construction of a large hydrogen production, storage, and distribution system for the hydrogen bus fleet in Aberdeen, showing further interest in utilities working in the hydrogen transportation sector (Scotland's 2020 Climate Group, 2015).

HYDROGEN RESEARCH AND ALTERNATIVE APPLICATIONS

Utilities may not yet be major players in the field of hydrogen transportation, but some power companies are actively working to advance the field and investigate other applications through research projects. With many governments hoping to advance the state of fuel cell technology and increase the supply of hydrogen, utilities may have the expertise and resources to become research partners and host pilot projects. This section highlights some of the programs underway in this area.

North America. Several utilities in the United States are exploring the potential of hydrogen in contexts such as power to gas, injection into the natural gas grid, and distributed generation. One major proponent is the Southern Company, which operates utilities across the states of Georgia, Florida, Alabama, and Mississippi. The Southern Company has made hydrogen a focus area at their Energy Innovation Center in Atlanta, where they are investigating generating hydrogen with excess energy and even creating a hydrogen distribution system throughout the region for transportation and industry applications (Swartz, 2015). Another notable development is occurring in New York State in the aftermath of Hurricane Sandy, where several towns, supported by municipal utilities and transmission operator National Grid, are in the process of installing stationary fuel cells to power microgrids (Curtin & Gangi, 2015).

Europe. As mentioned previously, utilities across Europe have led the development of power to gas systems, and these companies have also been very active in researching fuel cell technologies. In Germany, E.ON and EnBW have both constructed utility-scale fuel cells capable of running on natural gas or hydrogen, and RWE is working with Siemens to improve hydrogen storage and use hydrogen with captured CO_2 to produce chemicals (Bünger et al., 2014). In Norway, Statkraft was an early proponent of fuel cells; it helped to create a national roadmap for hydrogen transportation development and has since sponsored several fuel cell research and demonstration projects (Ryan, 2013).

In other parts of Europe, utilities are exploring other uses for hydrogen. Enel, the largest utility in Italy, operates the world's first hydrogen combustion power plant near Venice, which uses hydrogen generated at nearby refineries and factories to produce clean energy (Moloney, 2010). In the United Kingdom, Northern Gas Networks has studied the idea of replacing all natural gas with hydrogen in the city of Leeds and the challenges of using hydrogen within existing gas networks (Hull & Jones, 2016). Although these projects do not directly support fuel cell vehicles, they could help to build the hydrogen economy and drive down the price of related technologies.

VI. CONCLUSIONS AND OUTLOOK

Although electric vehicles currently account for less than 1% of global vehicle sales, the market is quickly growing, and many utilities are making progress in adapting to and supporting electric vehicle adoption. Around the world, power companies have built electric vehicle charging networks to build consumer range confidence and created programs to minimize grid impacts. There is still significant work to do in this field, but many automakers, EVSE and software companies, research institutions, and governments are working to accelerate vehicle-grid-integration. Different energy market structures and government programs have led to a wide variety of utility programs to support and adapt to ZEVs, but a number of trends and best practices have begun to emerge across jurisdictions.

High penetration of electric vehicles will have a significant impact on utilities, leading to a new source of electricity sales and new business opportunities. Many utilities and governments have worked proactively to study the impacts of electric vehicles on the grid and the best ways to incorporate ZEVs into their future plans. Although high electric vehicle uptake with uncontrolled charging could cause stress on the grid, these challenges are likely to develop slowly and can be avoided. The Sacramento Municipal Utility District concluded that smart charging will reduce the cost of distribution infrastructure upgrades by over $130 per vehicle by the time electric vehicles reach 6% market share (Berkheimer et al., 2014).

In order to avoid adding to peak demand and reduce upgrade expenses, utilities can passively promote grid-friendly charging behavior by adjusting electricity rate structures while avoiding pricing schemes that penalize electric vehicle owners. Many utilites have found that TOU rates offer a simple and effective solution; for example, SDG&E shifted over 80% of electric vehicle charging demand to super-off-peak hours (Cook et al., 2014). Further research from other California utilities, including PG&E, found similar results (Cook et al., 2014). More sophisticated rate structures have potential for even greater benefits, but face regulatory and logistical challenges.

In order to extract maximum benefits for utilities, consumers, and the environment, smart charging programs are needed. Simple smart charging programs, such as demand response, have been demonstrated in large trial projects. However, there are uncertainties about the economic viability of more complex technologies such as V2G, which would require more advanced technology and aggregation programs. Further development of these smart charging programs could yield not only greater grid stability and higher usage of renewable energy, but also financial benefits for electric vehicle owners through the provision of ancillary services: Some studies and trials have shown values of thousands of dollars annually for selling electricity back to the electrical grid at key times.

While there are many promising opportunities for utilities to support ZEV adoption, regulatory and technical uncertainty may discourage investment. One notable example is the issue of utility-owned charging networks, which are common across Europe, China, and Canada, but are only beginning to emerge in most of the United States. Similarly, a lack of standards in EVSE hardware and software has added complication to utility programs, although efforts are underway to rectify this uncertainty. In the Netherlands, all public Level 2 charging points have incorporated OCPP, allowing vehicle owners to use and pay at any station without owning separate memberships (Bakker & Trip, 2015).

Efforts to bring this standardization to other parts of Europe and North America could lower barriers for electric vehicle owners, businesses, and utilities alike.

Utilities are increasingly exploring new programs involving hydrogen, which may encourage uptake of hydrogen fuel cell vehicles. One prominent program is power to gas, which uses excess renewable energy to generate hydrogen through electrolysis. Demonstration projects have been built in Germany, the Netherlands, and California, and expansion of this practice could increase the hydrogen fuel supply as well as the profitablity of renewable energy. Power companies have found other unique ways to engage with hydrogen, both for transportation and energy purposes, and greater proliferation of hydrogen vehicles could spur further interest in hydrogen fueling and distribution.

Figure 3 shows a summary of the high-level findings in this literature review. In the figure, these findings are broken into three steps: preparation for incorporating ZEVs into the region's electrical system, implementation of best-practice programs to support uptake, and realization of many benefits for utilities, ratepayers, ZEV drivers, and the environment. All policies and results will depend on the local context, but these general lessons are important in showing that support of ZEVs is both feasible and beneficial for utilities.

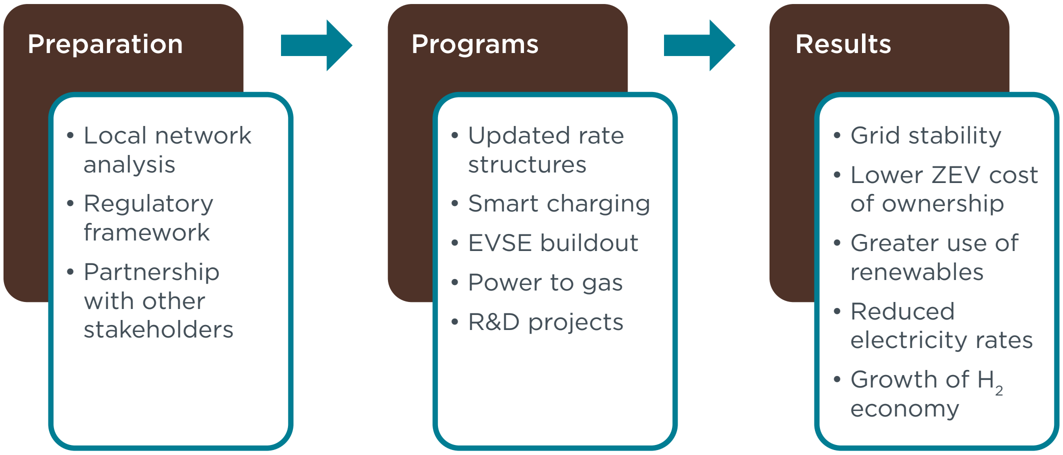

Figure 3. Summary of best practice steps for electric utilities to promote zero-emission vehicles

POTENTIAL AREAS FOR FUTURE RESEARCH

A number of ongoing projects involving utility-owned or -funded EVSE networks and smart charging may help to further refine best practices. However, there are still many other questions for utilities working to support ZEVs as new technologies are developed and these vehicles gain greater market share. Some topics for further investigation suggested by this literature review include:

Quantifying benefits of electrical grid services. Several studies and trials have estimated the value of electric vehicle services to the grid, including ancillary services sold on the market and reduced generation costs. However, these estimates have typically focused on one single market (such as one ISO market or one country in Europe) and describe only one aspect, leading to inconsistency in estimated benefits for electric vehicle users and utilities. A more generalized, complete model of the value of vehicle-grid integration, including grid services, battery impacts, climate benefits, and credits from other low-carbon policies, could be helpful for regulators, utilities, and businesses hoping to develop these programs. This type of cost-estimation model would also be important for estimating the total cost of operation for typical electric vehicle users. Clear guidance about the value of the most promising programs could help to reduce the sense of uncertainty and inaction among regulators, utilities, and OEMs in this field. The benefits calculated could ultimately become more important as consumer purchasing incentives become unavailable.

Grid impacts of DC fast charging and potential mitigation actions. Home and workplace charging, which largely use Level 1 and Level 2 chargers, currently account for the vast majority of charging events, and this trend is likely to continue with higher electric vehicle uptake. However, DC fast charging is important for building consumer range confidence and enabling longer travel distances, and could become more popular if costs decrease and specific sectors, such as taxis, delivery fleets, buses, or heavy-duty vehicles, become electrified. As fast charging networks expand and new technology enables greater charging power, their extremely concentrated and stochastic loads are likely to cause more of an issue for the electrical grid, and typical smart charging programs are less suited to this application. Further exploration of the impacts of DC fast charging and potential models to mitigate these effects could help to reduce costs and spur sustainable growth of fast charging networks, which would ultimately benefit electric vehicle owners.

Regional needs for smart charging. Smart charging is a promising way to increase the value of electric vehicles and may be able to substantially improve the stability and reliability of the electrical grid. However, the needs for smart charging depend significantly on the regional energy generation portfolio, physical grid infrastructure, and electricity market structure. For example, areas that rely heavily on wind and solar power would benefit substantially from timing electric vehicle charging to these intermittent resources, while regions that primarily use hydropower are able to easily ramp generation up or down based on demand. Closer analysis of how smart charging (either one-way or two-way) can be linked with renewable resources and contribute to more stable distribution systems in different regions may help to guide policy and technology development to accelerate vehicle-grid integration.

Analysis of power to gas applications to hydrogen transportation. The majority of hydrogen generated in utility P2G programs is injected into the natural gas pipeline network, and little work has been done to connect this technology to hydrogen vehicles. Most fuel hydrogen today is obtained from fossil-fuel sources, and alternative sources (such as P2G) are required to make fuel cell vehicles clean over the entire life cycle. Analyzing the feasibility of P2G programs to power a future hydrogen vehicle fleet, including matching current and projected renewable energy to transportation needs and considering storage and distribution requirements, may illuminate a path towards true zero-emission hydrogen transportation.

FUTURE OUTLOOK FOR POWER UTILITY SUPPORT OF ZERO-EMISSION VEHICLES

The success of electric vehicles relies in part on the support of utilities, which are at a minimum the daily fuel providers for electric vehicles. Utilities can play an active role in lowering the cost of ownership and increasing the environmental benefits of electric vehicles if the proper programs and technologies are in place. Conversely, if utilities fail to plan for electric vehicles or adopt unfriendly policies, they could hamper electric vehicle adoption and raise costs. Additionally, utilities could substantially improve the supply and distribution of hydrogen, enabling growth of the fuel cell vehicle market.

Utilities may come to rely on ZEVs as substantial and predictable electric loads with many ancillary benefits. Electric vehicles and hydrogen generation offer reliable and flexible sources of growth in an age of greater energy efficiency and distributed generation, and if properly managed, they can be an inexpensive provider of ancillary services to balance the grid. Although many utilities have focused on the potential costs of distribution system upgrades, awareness of the numerous benefits of utility electric vehicle support is increasing. The production of hydrogen could allow utilities to utilize spare renewable energy, but hydrogen vehicles will likely be necessary to make a large supply of hydrogen profitable. Utilities around the world have developed progressive and innovative programs to promote the success of these technologies, as this paper has discussed.

It is becoming increasingly clear that greater utility involvement in plug-in electric vehicles and related infrastructure can be beneficial for all stakeholders. Likewise, hydrogen may offer utilities a chance to support ZEVs and grow their business. As ZEVs continue to proliferate, it is likely that utilities will increasingly engage with the vehicle sector and build on the programs described here. Although there are certainly still technical and regulatory barriers and outstanding research questions, it seems likely that utilities will become important partners in the transition to a ZEV fleet.

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LIST OF ACRONYMS

AC	Alternating current
BSL	Battery second life
CO2	Carbon dioxide
DC	Direct current
DCFC	Direct current fast charging
DER	Distributed energy resources
DR	Demand response
EVSE	Electric vehicle supply equipment
ISO	Independent system operator
IT	Information technology
LCFS	Low Carbon Fuel Standard
P2G	Power to gas
PUC	Public Utility Commission
RTO	Regional transmission organization
TOU	Time of use
V2G	Vehicle to grid
VGI	Vehicle-grid integration
ZEV	Zero-emission vehicle