Electric Vehicles as Grid Support

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Abstract The vision of Electric Vehicles (EVs) providing energy back into the grid is one that has captivated people since the re-emergence of EVs and the rise of the Smart Grid. In this vision, EV owners, electricity network operators and society more generally share the benefits of smoothing the peaks and troughs of electricity demand and improving EV battery utilization. Whilst technical obstacles remain, the greatest limitations are those presented by electricity market rules. Within existing frameworks, charging can be managed according to network needs for widespread benefit. And more immediately, vehicles can supply emergency back-up power or act as local storage for renewable energy through interactions that take place behind the electricity meter. Successful deployment of these scenarios will serve as a stepping stone towards the future vision of EVs as grid storage.

Keywords Electric vehicles · Electricity networks · Charging · Vehicle-to-grid · Demand response

1 Introduction

The resurgence of electric vehicles has coincided with a period of unparalleled change in the electricity sector. Advanced monitoring, analysis, communications and control, distributed energy resources and various other innovations are being adopted at the local, regional and national level for efficiency improvements, improved energy access and reliability, and reduced environmental impacts.

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The coincidence of these technological developments have given rise to the vision of a fully-integrated electricity and transport system, where electric vehicles provide convenient storage of cheap, clean electricity for later re-use. This vision addresses the previously inefficient allocation of resources that is stationary vehicles, while at the same time facilitating greater integration of intermittently-generated renewable energy.

This compelling ideal has captured the public imagination beyond simply futurists, academics and technophiles. The endgame for some—to go “off the grid” and be free from the yoke of utilities and oil companies—is encapsulated by the prospect of an EV parked in the driveway of one’s home under a roof covered in solar cells.

However, to realize this vision a range of technical, economic and regulatory obstacles must be surmounted. Integrating vehicle batteries into grid operation; developing business models that address capital-intensive technology investments; and deploying solutions within current regulatory frameworks are significant challenges that will not be addressed overnight.

Progress is being made. Lessons learned from the first phase of EV deployments are informing technical design and standards for the next-generation of grid-interactive vehicles. Niche applications that could potentially support a positive business case for vehicles as storage are being explored. Electricity network operators are gaining confidence in their ability to accommodate, and even benefit from, electric vehicles.

This article steps through the features of electricity grids and electric vehicles relevant to their interaction. It explains the likely use-cases for managed vehicle/grid interactions based upon the overlapping characteristics of the two technologies and their operational environments. And through an improved understanding of the issues and opportunities, the article will set out pathway towards realization of the integrated-system vision set out above.

2 How Do Electricity Grids Work?

In many people’s mind “the grid” is a proxy for the system—electrical or otherwise—encompassing the society in which they live. However for the purposes of this article, the concept of a grid is defined in terms of the building, precinct, or regional-scale network connecting electricity sources with end-uses.

Design and operation of electricity networks revolves around the (often competing) objectives of reliability, affordability and sustainability.

Reliability reflects the continuous provision of electrical supply of the appropriate quality. When demand exceeds supply, system failures in the form of outages occur. When the quality of electrical supply goes outside of agreed limits (e.g. for frequency or voltage), equipment malfunctions (e.g. machinery running slower) or even failures can result.

Efforts to ensure system reliability and sustainability meet required levels must be considered alongside the costs associated with these investments. To ensure affordability, community-scale electricity is generally supplied within a market framework that seeks to balance costs and service levels, now and in future. Commonly this will place decision-making for network prices with an independent regulator, who will consider investment proposals from monopoly network operators on behalf of customers. As electricity networks are capital-intensive assets operated over decades, extensive regulatory frameworks provide clarity for all parties around the rules, costs and benefits for their interaction.

Activities such as on-site (distributed) energy generation are regulated in terms of their interaction with the overarching network. However, where activities are entirely "behind-the-meter" (refer to Figs. 1 and 2), decision-making is largely in the hands of the customer. By taking ownership of the reliability, affordability and sustainability of their network, the customer can strike a different balance between these objectives from the more utilitarian approach taken on their behalf in the regulated market.

An important influence on the design of electricity networks is the forecast needs of users. Accordingly, peak demand is a major driver for network investment [1]. Demand management is increasingly seen as an important tool to reduce the need for network investment and minimize the costs of electricity for users. Regional-scale networks pursue demand management programmes to varying degrees, primarily as a reflection of market rules which incentivize or obligate them to do so.

The majority of the benefits from demand management are obtained by focusing on managing loads during relatively infrequent periods of peak demand [2]. And as part of efforts to minimize transaction costs, demand management has traditionally focused on a relatively small number of large loads—for example commercial/industrial energy users rather than residential.

The digitalization of electricity networks is providing enhanced visibility, decision-making and control as part of the move towards "Smart Grids". In parallel, pricing structures are being implemented that better incentivize demand management. Technology cost reductions for renewable energy generation and energy storage are driving uptake and market reform. These developments are in pursuit of better outcomes relative to the system objectives of reliability, affordability and sustainability.

3 What Are the Characteristics of Electric Vehicles Relevant to Grid Support?

For the purposes of this article, an electric vehicle is defined as a vehicle that draws some or all of its propulsion energy from an external source via a plug (i.e. this definition excludes conventional hybrids). Although the latest incarnation of EVs as mass transit vehicles is relatively new and fast-evolving, they have some defining characteristics that are relevant to their interaction with electricity networks.

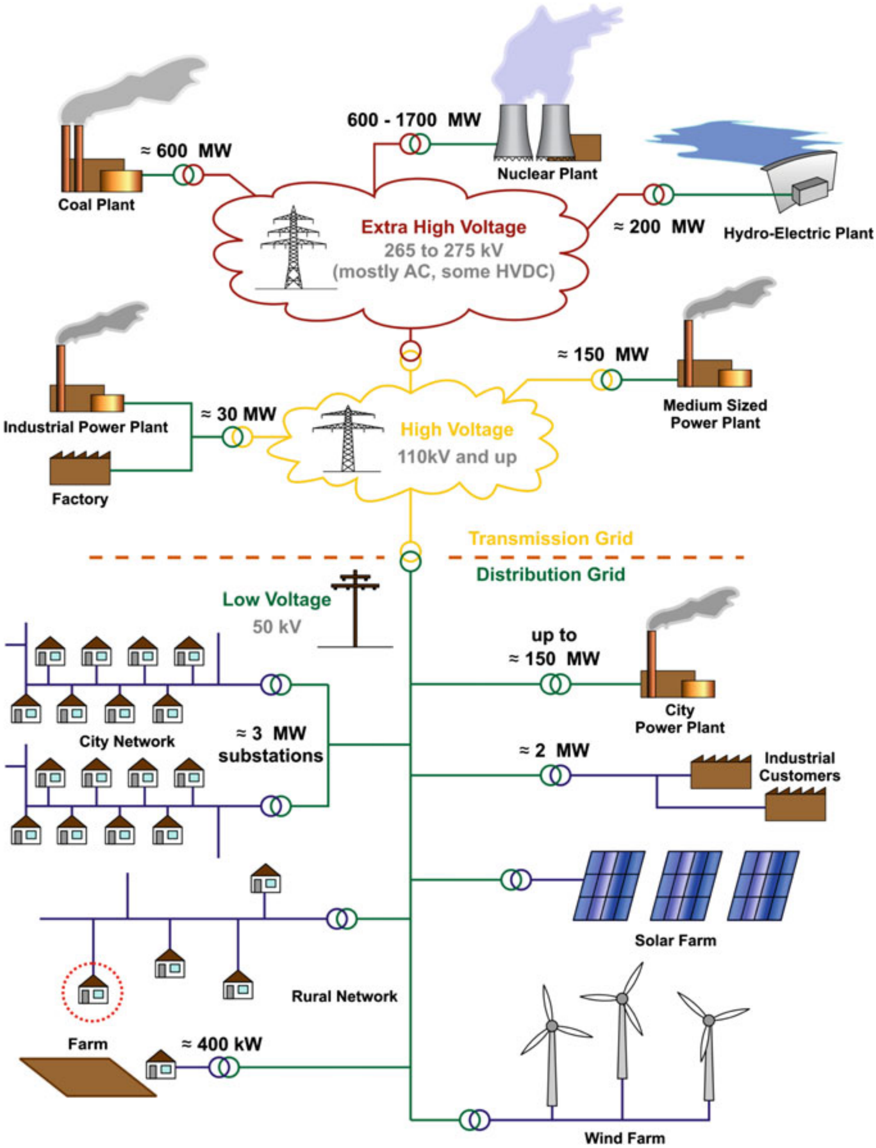

Fig. 1 A regional-scale electricity network of interconnected sources and end-uses that corresponds to the most common definition of "the grid", where a single home has been circled to provide context for Fig. 2

A key issue for vehicle/grid interactions is the primary application of the vehicle as transport. When and how far a vehicle is driven or planned to be driven determines when and how long the vehicle is plugged in, how quickly it is expected to charge, and how much charge it draws or is available to supply. Generalizations

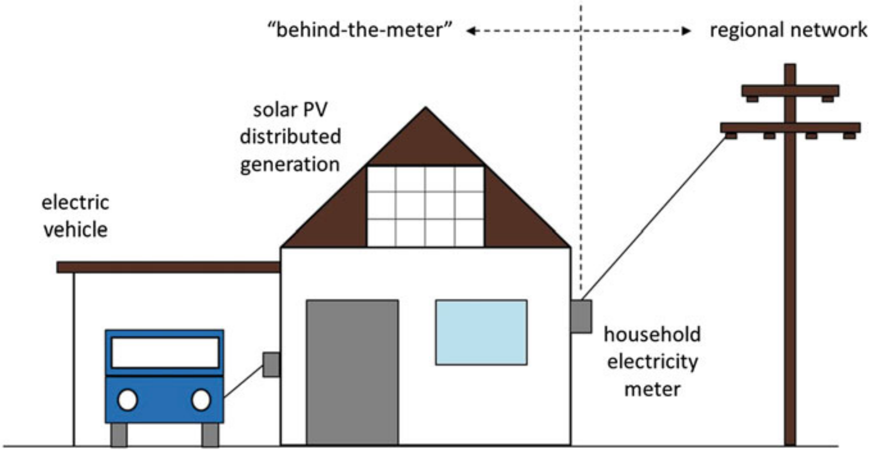

Fig. 2 A residential electricity network including grid-connected distributed generation and a plug-in vehicle. This network exists "behind-the-meter"—the demarcation point with the regional network as illustrated in Fig. 1

based upon the experiences and opinions of the first generation of EV owners include [3, 4]:

- Private vehicle owners primarily charge overnight by plugging in upon their arrival home and unplugging prior to setting off the following morning.
- Charging behaviour by private vehicle owners is responsive to price signals such as off-peak tariffs or free charging opportunities through the workplace, but is ultimately subservient to the vehicle utility.
- Fleet vehicles are highly variable in terms of their distance travelled and charging patterns, and there is a disconnect between fleet vehicle users and those with responsibility for electricity costs within fleet operations.
- Distances travelled between charging events are significantly less than the potential range of the vehicle when fully charged, and charging events are completed within the time available before the vehicle is next required for use.
- Quick-charging provided as a commercial service is used for emergencies rather than as the primary charging strategy.

While these generalizations are useful, it is important to note they are not strict rules as behaviour can vary markedly as a reflection of vehicle use requirements.

The storage capacity of electric vehicles varies—from 16.5 kWh in a GM Volt plug-in hybrid EV [5], to 24 kWh in a Nissan LEAF fully-electric vehicle [6], 85 kWh for the largest battery size offered in a Tesla Model S [7], and 324 kWh for a BYD electric bus [8]. Given that the average American home uses around 30 kWh of electricity per day [9], a plug-in passenger vehicle has the potential to add substantially to household electricity demand, or conversely to provide energy for several days if rationed.

The traction battery is the single most expensive component within an electric vehicle, costing thousands of U.S. dollars to replace [10]. While under normal operating conditions the battery will last for around 8–10 years [11], there is the potential for battery life to be reduced by variables within the operating environment. This may translate to warranty restrictions that re-allocate risk for owner-determined operating decisions, accelerated vehicle depreciation or a general reluctance from manufacturers to embrace vehicle-as-storage applications.

Battery packs prefer to operate within a relatively narrow temperature range, and can be damaged irreparably by extremes of temperature. In addition to the influence of ambient temperature, the electrochemical reaction that is at the core of battery technology results in the production of heat.

The complex interaction of these variables is managed by the vehicle Battery Management System (BMS), and translates to varying rates of charge/discharge within a single cycle and across separate cycles. Even within the operating parameters permitted by the vehicle BMS, battery life will be decreased by regular deep-discharging and/or fast-recharging—potential examples of owner-determined operating decisions.

At the high end of the variation within the charging cycle, peak power levels for EV charging can be significant. Home charging peak power loads are generally one of either 3.3 or 6.6 kW [6] but may go up to 20 kW [7]—any of which will be a significant addition to household electricity demand. This is significant due to the correlation between charging behaviour and household energy demand in the absence of other influences.

Commercial quick-charging (12–50 kW) [12], or charging for electric vans, trucks or buses (up to 200 kW) [8] is more significant again in terms of its potential impact upon the grid.

Charge management technologies are also relevant to consideration of EVs for grid support applications. Interactions between the vehicle, network and user systems will rely upon consistent application of technical standards at each interface. Vehicles may be equipped with (proprietary) charge management technology, including charge timers and smartphone applications that provide remote charge monitoring and management. Where absent from the car, dedicated charging equipment or building energy management systems may provide this capability.

For use as storage, vehicles must be capable of exporting energy back into the grid. Furthermore, the charge supplied must be compatible with the grid, and managed so as to reflect the needs of both the grid and the vehicle owner, within the constraints of the vehicle BMS and battery life impacts.

Bi-directional vehicle charging and charging infrastructure systems are emerging from technology providers [13, 14]. These systems deal with many of the technical challenges of extracting charge and supplying it into the grid, and are being tested within real-world operating environments. Additional work is underway on standards to assist with the regulatory issues associated with supplying energy into the grid [15] and integration with network management systems [16].

4 How Could EVs Provide Grid Support?

In considering the characteristics of plug-in vehicles as they relate to grid support, the scope of this article has been refined to focus specifically on intact and operational vehicles. This excludes applications where the traction battery is removed from the vehicle and utilized as stationary storage under "battery swap" operating models or as part of a "second-life" beyond its first life in the vehicle.

Building on this, the potential grid support applications can be considered in the context of a range of high-level costs and benefits.

The costs include the impact upon the vehicle utility, the impact upon battery life/vehicle re-sale value, and the technology (capital) and transaction (operating) costs for all stakeholders.

The benefits relate to avoided costs associated with grid investments to deal with peak demand increases, improved network capacity utilization from charging demand management, and potential uses and benefits arising from electricity stored in and sourced from the vehicles.

Once applications have been identified where there is an overall net benefit, the distribution of costs and benefits must be managed equitably within the system. For ease of implementation, this should happen through existing regulatory and market arrangements. Key enablers may include market rules which provide incentives for demand management or allow for stored energy to be supplied into the market. In the absence of enablers for market participation, behind-the-meter applications may be considered as a closed system.

Within this conceptual framework a number of applications have emerged that are presented in order of their ease of deployment.

4.1 Off-peak Charging

As outlined in Sect. 3, electric vehicle charging has the potential to add significantly to peak demand at the household level and in aggregate for regional-scale networks. If unmanaged, studies have found that network augmentation may be required once EVs are adopted by 10 % of households [17].

EV charging behaviour has been found to be responsive to price signals [18]. Time-of-Use (TOU) rate structures incentivize electricity to be used in off-peak periods—a form of demand management known as Demand Response [19].

EV charging activities are responsive to TOU incentives on account of the low impact on the driver in terms of their vehicle use, the technology solutions which enable easy and convenient charge management, and the significant benefit to them in terms of reduced electricity costs. Drivers respond to TOU rates by programming their charging to begin at the onset of the off-peak period—minimizing their costs without impacting their vehicle utility.

For the network operator, off-peak charging can be achieved through the provision of a TOU tariff as part of a DR programme. Historically, DR programmes have focused on commercial/industrial customers, however in many markets programmes now also apply to residential customers. The benefits relate to avoided investment in generation and/or network infrastructure to support additions to peak demand arising from EV charging. These savings translate to lower costs for all electricity users.

4.2 Optimized Charging

Optimized charging activities using Load Control (LC)—another form of demand management—allow the peaks and valleys of electricity demand to be addressed and the impacts of intermittent supply from renewable sources to be mitigated (refer also to Sect. 4.4 below). By more closely matching demand with supply and/or reducing demand fluctuations, supply interruptions may be managed, network asset lifetimes can be prolonged and maintenance costs reduced.

In addition to market rules that allow for and incentivize LC interactions, end-to-end technology solutions are required for charging to be managed from the network perspective. Vehicle charging loads should be visible and manageable to the network operator, who can then optimize charging in line with the wider network needs. This is most easily achieved via grid-integrated charging infrastructure that forms an extension of the Smart Grid.

The costs for an end-to-end technology solution have been found to be around one tenth the cost of network augmentation under an unmanaged charging scenario [17]. By optimizing vehicle charging, generation can be shifted to cheaper plants and influences the choice of new plants [20]. Studies have shown that by optimizing charging, over 50 % of households might adopt EVs without network augmentation being required [17].

However, a threshold issue for optimized charging in regional-scale grids relates to the ability and incentives for network operators to pursue demand management approaches. In addition, whoever makes the upfront investment in the grid-integrated charging solution needs to be able to recover the costs as part of the benefits distribution. For example, Italian market rules define grid-integrated charging outlets as part of the cost-recoverable utility asset base of the network operator [21].

Results from field trials suggest that driver acceptance of network-managed charging reflects such issues as their ability to override the managed charging activity (even at a cost), remote visibility and control over their charging, and information and clarity in relation to the managed charging activities (for example, that their vehicle will be fully charged by no later than 7 am) [22].

With the advent of advanced network control systems, transaction costs may now be reduced to allow the wider benefits associated with optimized charging to be realized [19]. In addition, the negative impacts associated with the creation of a "second peak" in electricity demand coinciding with the beginning of the off-peak tariff period may be avoided.

Within the LC framework drivers will manage their vehicle charging and use to avoid cost penalties and maximize benefits, but may elect to override LC events should their situation require it. For LC programmes focused on load reduction from air-conditioners or heating units during peak demand periods, the consumer typically receives a benefit of $USD 50–100 / year as a credit on their electricity bill [2]. This may be reduced or even exceeded by penalties associated with opting out of the LC events.

Optimized charging may facilitate renewable energy integration through closer matching of demand with supply [23]. For site owners with distributed generation, the EV can provide an alternative to feeding surplus electricity back into the grid [24]. This may be particularly relevant in the absence of a feed-in tariff for excess electricity [25].

4.3 Grid Storage for Emergency Back-up

As outlined in Sect. 3, electric vehicles have sufficient storage capacity to provide emergency power for several days if rationed in the event of wider system failure. This is a potentially high-value, even life-saving, application of electric vehicles as storage. In addition, as the energy is used local to the vehicle, transaction costs are minimal. This opens up the possibility of using EVs as a standalone "off-grid" power source, for instance during recreational camping.

In its simplest form, the use of EVs as a source of emergency back-up power can be achieved through devices that allow power to be supplied direct from a vehicle to small appliances, such as lighting or mobile phone chargers. This equipment generally converts the DC charge from a vehicle into a useable, if small, AC power supply approximating mains electricity independent of a hardwired electricity network [26, 27].

Once a vehicle is connected to a network, the appropriate controls, switches and protections must be present for it to act as a source of supply [28]. The network being served must be isolated, and the use of emergency power must be easily and clearly made known to avoid endangering anyone at work on the surrounding network, for example line-workers who are attempting to restore mains power [29]. Advice is generally available from the regional network operator on applicable standards and regulations.

At the top end of the scale in terms of cost, complexity and capability are standalone network operations that incorporate distributed energy resources (DERs). Microgrids—independently capable and controllable networks which include DERs and potentially storage—are of growing interest as a means of providing system resilience [30]. The inclusion of EVs as storage within these networks may ultimately prove to be a more important application than for the macro-grid [31].

4.4 General Grid Storage

Utilizing stationary electric vehicles as a storage facility for the grid is a simple, yet powerful vision. This model is what many consider to be the definition of Vehicle-to-Grid (V2G), a term which may apply to regional-scale network interactions alone, or may also include smaller system interactions known as Vehicle-to-Building (V2B) or Vehicle-to-Home (V2H). The challenge facing proponents of this vision lay in the investment risk arising from the uncertain benefits, particularly when considered alongside non-vehicle storage solutions.

The technical solution to utilize electric vehicles as grid storage is an enhanced version of the network-connected emergency back-up solution from Sect. 4.3. Regular, bi-directional energy flows can be managed using control systems that are evolving for more widespread application. Complex, automated monitoring and decision-making is increasingly possible through Smart Grid [32, 33], Building Energy Management (BEM) [34] and Home Energy Management (HEM) [35] systems. As outlined in Sect. 3, charge extraction on the vehicle-side will occur within the constraints of the BMS and through consistent application of technical standards each side of any sub-system interface.

The complication within this system relates to the control strategy that must reconcile the constantly-changing and potentially-competing uses of the vehicle as transport and grid storage. The response to this dynamic is constrained by the time required for meaningful charge transfer to take place—itself a variable controlled by the BMS.

As outlined in Sect. 4.2, drivers may be comfortable with managed charging of their vehicle so long as they retain ultimate control to ensure they have charge when they need it [22]. Furthermore, research suggests people discount potential revenues from V2G contracts heavily, and associate V2G with high inconvenience costs [36]. While these findings may be unsurprising in a market with practically no knowledge of V2G arrangements or operation, they highlight the challenges inherent to the V2G operating model.

The design of demand management programmes may provide some insights into the likely path forwards for V2G. At the outset, market rules must enable and incentivize the participation of energy storage, including from vehicles [37]. Under this scenario, grid storage capacity must be committed ahead of when it is provided. This will necessitate high confidence levels around the amount of charge that may be supplied in line with scheduling by the grid operator—a requirement that may conflict with the primary use of a vehicle as transport. Service agreements designed around the likely overlap between grid needs and vehicle charging connection may help address this and improve the potential for EVs to provide meaningful grid storage capacity.

Demand management programmes focus on interactions that minimize transaction costs relative to the value of the energy exchanged. For V2G this may mean corporate vehicle fleets able to be treated as a single storage facility, commercial vehicles with relatively large storage capacities, and/or private vehicles in homes aggregated by energy service companies in utility regions where a critical mass of vehicles is present.

Use of this storage capacity will likely align with peak demand periods when electricity prices are higher [38]—typically in the early evening. The coincidence of this period with the return home from work may inform the design of the service agreements as outlined previously. Although there is much variation within and across markets, one study that drew on peak power costs for California suggested that the business case for V2G is marginal [38].

While a generalized approach delivered under a service agreement aimed at peak power applications may enhance V2G viability, the outcome will by necessity underutilize the potential grid support of individual vehicles. Conversely, V2G within a smaller, closed system under the management of a single entity may provide greater benefits for a similar investment in the enabling technology.

Corporate fleet vehicles operating out of owner-occupied premises [39, 40] or private vehicles garaged at home may provide building energy support and improved vehicle asset utilization through user coordination across their electricity and transport needs [41]. This scenario becomes increasingly relevant when the objective is to enable larger amounts of renewable energy to be integrated—refer to Sect. 4.5 below.

Finally, a comparison with stationary storage solutions is important in any consideration of the path forwards for V2G. Purpose-built grid storage facilities will provide scale, reliable access, and utilize battery designs optimized for the task (for example, flow batteries are an emerging technology particularly well-suited to grid capacity storage) [42]. While the use of plug-in vehicles for storage improves utilization of an existing asset, preferential allocation of vehicles to transport tasks may undermine their competitive position for grid support [43].

The obvious solution may therefore be a complementary arrangement between stationary energy storage facilities and electric vehicles [44]. Stationary facilities may provide the main form of grid storage that is in relatively constant use, while vehicles may be called upon for only the highest value/least frequent storage applications—this is partly the thinking behind ancillary services applications explained in Sect. 4.6. This approach recognizes the contrasting characteristics of the storage technologies, the lower unit power supply costs of stationary storage, and the opportunity to realize additional value from investment in vehicles.

4.5 Grid Storage for Renewables Integration

Affordable energy storage is increasingly viewed as the key enabler for large-scale renewable energy [45]. The intermittent, variable supply characteristics of renewable energy resources create significant challenges for their integration into the grid and widespread adoption. These obstacles may be surmounted by storing energy during periods of oversupply for later re-use or to provide compensation for power quality impacts (which are dealt with as ancillary service applications in Sect. 4.6 below).

As has been described previously, the main limitation to this vision lay in the competing uses of the vehicle. Patterns of vehicle use are unrelated to those of renewable energy generation, suggesting that the requirements for renewable energy storage may be often incompatible with the availability of stationary vehicles. This obstacle may be partly countered through optimized charging strategies [20] that take advantage of EVs to store surplus renewable energy for use in transport, rather than supply back into the grid (refer also Sect. 4.2).

At the macro scale the continued uptake of both technologies will allow the variability of individual resources to be accommodated and taken advantage of across a regional network [46]. As more EVs are adopted and made available as a supplementary storage resource alongside stationary facilities, the growing and flexible storage capacity will facilitate larger amounts of renewables [45]. Coordination of the ever-expanding number of complex grid resources will be handled by the continued evolution of Smart Grid control systems.

At the other end of the scale, the benefits of allying the technologies within smaller-scale systems at the precinct, campus, building or home level can be captured by a single entity. This may encourage adoption due to direct and indirect financial, social and environmental benefits [47].

For example, the optimized charging strategy touched on above may allow system operators to maximize the benefits of their renewable energy production. This outcome will reflect a range of factors including purchased electricity costs, feed-in tariffs, and conventional transport fuel costs [25, 48].

Careful accounting and reconciliation of energy production and use may also inform greenhouse gas mitigation strategies, and by extension brand-building efforts in the eyes of key stakeholders. Technology providers have already begun to exploit this vision as a means of promoting their products [49].

As an extension of this, the allure of "going off the grid" should not be underestimated [50]. With solar generation making the transition to mainstream adoption in many markets, these homeowners are engaged in their energy use and receptive to the integration of an EV into their home [51]. Early-adopters will pay a premium in terms of cost and effort to attain a technology-rich, low-carbon lifestyle which is technically possible right now (particularly when coupled with a stationary storage solution). Less-costly, more user-friendly solutions will have increasing appeal in the face of rising network connection costs that are unfolding in many markets.

4.6 Grid Storage for Ancillary Services

Grid operators use ancillary services to maintain stability and reliability in the face of dips and surges in the balance of electricity supply and demand [23]. There are a range of ancillary service products that reflect the varying timescales over which this response is required, including frequency response, spinning reserve, regulation and load following/ramping. Due to the specific and critical needs addressed by ancillary services, their value tends to be significantly higher than equivalent amounts of energy supplied as capacity. Payments for ancillary services include payments for availability and for delivery [52].

Electric vehicles as grid storage resources are potentially well-suited to ancillary services that require fast response times and are of short duration [53]. These requirements are a good match for EV storage technology characteristics, and are less constrained by the limitations on EV storage volumes and depths of discharge.

Participation in ancillary services markets, if permitted under the market rules, would likely take place via an energy aggregator such that the capacity of multiple vehicles could be pooled and traded into the market. Opinion on the business case for EVs as a resource within ancillary services markets varies [38, 53].

5 The Path Forwards

Establishing a roadmap for EVs as grid support begins with an understanding of the electricity market. The rules and regulations applicable to grid and market operation are a threshold issue for the use of EVs as grid support. They set out what is permitted, very often determine the associated financial value, and strongly influence the distribution of costs and benefits across the value-chain.

As was outlined in Sect. 2, market design and operation varies from region to region. This has implications for technology and service providers, as the market opportunity must be significant enough to warrant their investment. The path forwards for EVs as grid support is likely therefore to reflect the arrangements and market-forces prevailing across the largest markets for the vehicles.

On this basis the near-term trends will be likely determined by the U.S. market, particularly California (the region with the highest plug-in sales globally, the operation of which takes place within the Californian electricity market) [54]. As the Japanese and EU markets receive largely the same plug-in vehicle makes and models as the U.S. (unlike China), issues and opportunities common to all three markets will also be a factor in the development plans of technology providers.

Efforts to address peak electricity demand are translating to consideration or application of Time-of-Use (TOU) tariffs in these markets. Cars are generally supplied with the capability to manage charging so that drivers can take advantage of these tariffs easily and conveniently. Although there are barriers to the adoption of TOU tariffs in markets where they have not already done so [55], the low costs and high value associated with the promotion of off-peak charging for EVs is likely to translate to alignment with EV uptake.

Some U.S. utility regions are also operating direct load control as an option for a number of electrical loads. Although no markets currently incentivize or operate this for EV charging management, in November 2013 the Californian electricity market regulator initiated rule-making to examine “the potential value to ratepayers and the electric grid of vehicle-grid integration, including the use of vehicle batteries for Demand Response or energy storage” [56]. This follows on from the

Californian mandate for 1.3 GW of batteries and grid storage by 2020 [57]. When combined with their market leadership in sales of plug-in vehicles, the effect of these initiatives will be to ensure that California is the lead market for EVs as grid support.

Should it transpire that there is a business case in favour of optimized charging and/or V2G interactions of whatever type, the likely pathway would be via third-party energy service providers experienced in the delivery of Demand Response programmes. These entities will aggregate vehicles [58] under service agreements that allow the service provider to participate in the wholesale electricity market. Ensuring a fair distribution of costs and benefits will require solutions to be found for the upfront costs of the technology enablers in each application. The findings of the Californian regulator from their investigation of vehicle-grid integration will inform any response which may address this issue and in doing so advance the market. Notably, optimized charging may provide a superior cost-benefit argument with less barriers to adoption than vehicles-as-storage applications [38, 53].

As behind-the-meter interactions are less influenced by the diverse, complex and slow-to-change electricity market environment, these applications may quickly surpass those revolving around market participation.

Vehicle-to-Home (V2H) technology progressed rapidly in Japan as an outcome from their response to the Sendai earthquake and associated events of 2011. In 2012 vehicle manufacturers released systems into the Japanese market that allow vehicles to be used for emergency back-up, such that the Nissan LEAF-to-Home system is now bought by around 7 % of Japanese LEAF drivers [59]. Although Japanese and North American electricity systems both utilize 110 V supply, vehicle manufacturers are yet to offer back-up systems for sale in the U.S. The availability of aftermarket EV back-up power devices in the U.S. suggests that this oversight may be temporary.

The emergence and continued evolution of the "Connected Home" combined with the growth in residential solar installations is likely to have consequences for V2H applications. Clean technology enthusiasts are likely to form the V2H early-adopter market who will pay a premium to align themselves with the powerful vision symbolized by these systems. To capture the early-mover advantages for their brands, V2H system providers may emerge fairly rapidly from the Japanese experiences with emergency back-up systems and/or strategic partnerships between Electric Vehicle and Connected Home technology vendors. These opportunities will combine with the convergence towards recognized technical standards (particularly for the Connected Home) to help accelerate development of V2H products.

At the nexus of regional-scale V2G applications and V2H sit Vehicle-to-Building (V2B) interactions within commercial/industrial applications. Although many of the V2H benefits above may be harnessed by corporates, the obstacles inherent to tenanted premises and the disconnect between the fleet/facilities managers and the actual drivers of the vehicles are a barrier to uptake. For corporates who operate plug-in fleet vehicles out of owner-occupied premises, near-term brand-building opportunities exist for V2B applications, even if these are likely to be scaled to a small number of vehicles. As the potential marketing benefits decrease with time, the business case for V2B against on-site stationary storage solutions must overcome the clear disadvantages relating to management of the combined functions of the vehicle as transport and storage.

6 Conclusion

Convergence of our electricity and transport systems has never seemed closer. The dream of many to become self-sufficient for their daily energy production and use seems more attainable than ever. These views are founded on the observation that technical solutions exist right now to allow for electric vehicles to be fully-grid-integrated.

The commercial reality is however more sobering. This paper has provided an explanation of the challenges to realization of the "off-grid" vision. Regulatory and financial obstacles must be addressed before electric vehicles will become a significant contributor to the Smart Grid.

Opportunities do however exist for a range of niche applications, such as back-up energy supply during times of emergency, along with optimized charging practices that will provide more widespread benefits. Through lessons learned along the way and the continued evolution of more affordable, effective technology, the ultimate goal for stationary vehicles to provide cost-effective grid storage may be realized.

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