The Role of Plug-In Electric Vehicles with Renewable Resources in Electricity Systems

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Abstract

Two technology options, renewable electricity generation and vehicle electrification, are being promoted to achieve two of the greatest objectives of this century: meeting growing global energy demand while reducing greenhouse gas emissions. Addressing both objectives implies shifting part of this energy demand away from fossil fuels to other primary energy sources. Renewables and plug-in electric vehicle (PEV) adoption have been hindered by significant challenges despite their known potential to improve energy sustainability in electric power systems and transportation. The two technologies have natural synergies between them, however: PEVs are a natural source of demand- and supply-side flexibility, which can help mitigate the negative ancillary effects of renewable variability and uncertainty.

In this paper we discuss the issues hindering renewable and PEV adoption and the synergies between these two technology pathways. Finally, we raise some issues with implementation and challenges with incentive and business plan design that may hinder fully realizing these synergies. We also propose some important research questions that would help address these implementation issues.

Keywords: Plug-in electric vehicles, renewable integration, power system operations

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1. Introduction

The world faces a growing energy sustainability problem, requiring energy sources that can meet growing demand in a sustained way into the future without compromising global climate and resources. In its most recent assessment, the U.S. Energy Information Administration (EIA (2013)) projects that world energy consumption will grow by 56% between 2010 and 2040. This demand is driven by long-term economic growth, much of which is forecast to occur in countries outside the Organization for Economic Cooperation and Development (OECD).

Indeed, energy demand in the OECD is forecast to increase 17% as opposed to 90% in non-OECD countries, where it is likely to be met through increased use of fossil fuels. Using three Intergovernmental Panel on Climate Change scenarios, Karl et al. (2009) demonstrate that this increase in energy demand and associated fossil fuel use can result in atmospheric CO_2 concentrations that are 22–111% greater than the level of 450 part per million at which global average temperature stabilizes.

In addition to environmental concerns, fossil fuels raise issues of security of supply due to unstable geopolitical relations and physical resource constraints. These problems result in direct and indirect costs to

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consumers and to the economy. For instance, a share of the United States' military expenditure is devoted to protecting oil supplies abroad. Lipman and Delucchi (2010) estimate that the military expenditures associated with securing oil supplies from the Persian Gulf add an average of $0.03 to $0.16/gallon to the price of gasoline. Sudden fuel supply disruptions can occur despite these efforts, causing price spikes and reducing economic output. The National Research Council (2010) estimates that the costs of oil supply disruptions have ranged between $1.16 and $15.01/barrel in the United States. Aside from the geopolitical risks for security of supply, fossil fuels resources are limited by the finite amount of hydrocarbons on Earth. Even as new fossil fuel reserves are discovered, they cannot always be economically extracted and exploited. The overall diminishing reserves increase fuel supply costs.

For these and other reasons, governments and other agencies around the world have begun searching for means to address this energy sustainability problem. Two technological solutions that have gained particular interest are renewable electricity sources and transportation electrification.

The EIA (2013) estimates that of the 553 EJ of world energy consumption in 2011, 39% was in the form of electricity. Moriarty and Honnery (2012) survey a number of studies estimating total global generation potential from renewable energy sources. These studies estimate between 246 EJ and 4842 EJ of generation potential. Renewable energy has the potential to improve energy sustainability in electric power systems and in the associated downstream activities and sectors. Moreover, transportation accounted for close to 20% of total world energy consumption in 2011, of which very little was electricity. Switching electricity generation to renewable sources can alleviate many of the problems associated with traditional generation feedstocks. Electrifying transportation can further leverage this switch in generation sources, since fossil fuels used directly in vehicles can be replaced with renewable electricity sources.

These technology solutions are not panacean, however. Both vehicle electrification and the use of renewable electricity sources raise serious technical, economic, and customer adoption issues.

Many renewable electricity sources that are commercially viable today have varying degrees of real-time supply uncertainty and variability. For instance, real-time wind speeds can be highly variable, due to complex interactions between weather fronts and other phenomena. These may be difficult to predict hours ahead, much less years ahead when capacity expansion decisions are made. Renewable resource variability and uncertainty raise a number of power system operations and planning challenges, since real-time electricity demand and supply must be in exact balance at all times to maintain power system stability and reliability.

Key questions stemming from renewable integration include:

- What is the renewable availability profile and how does it affect a power system's net load (*i.e.*, load less renewable generation) profile?
- How much conventional controllable generation is required to serve electricity demand without sacrificing power system stability and reliability?
- What are the energy supply cost impacts of renewables, including the cost of building renewable capacity and their effect on system operations?
- How do these impacts vary with renewable penetration and the technology mix used?

Transportation electrification raises its own sets of issues, especially for personal mobility use. From the consumer's standpoint, plug-in electric vehicles (PEVs) currently suffer a fixed cost premium compared to conventional vehicles. This is largely attributable to the cost of the battery, with 2013 estimates varying between $400/kWh and $800/kWh (Crist (2012)). Thus, the cost proposition to a consumer of switching to a PEV comes from the lower operating (driving) costs that eventually offset the higher upfront purchase price. The payback period of various PEVs varies across estimates and depends on other socio-political factors such as subsidies at purchase and petrol tax levels. Pure electric vehicles (EVs) further suffer from the lack of fueling infrastructure and the related 'range anxiety' phenomenon. 'Range anxiety' refers to drivers' concerns with the risk of being stranded with a discharged battery and with the delays to their journeys associated with long recharging times. Chéron and Zins (1997); Eberle and von Helmolt (2010); Franke and Krems (2013) find that many consumers are unwilling to purchase EVs if a 'safety net' of charging stations is not available. This anxiety has been found to lead to overly cautious charging behavior, as in the EV pilot conducted by the Tokyo Electric Power Company (TEPCO). TEPCO introduced a set of electric service vehicles, which were recharged overnight using 'slow' chargers at the TEPCO facility, for use over an 8 km × 15 km service area. They found that the EVs were used over a very small area around the facility and were typically returned to the station with a battery state of charge (SOC) much greater than 50%. A year later TEPCO installed a 'fast' charging station within the service area, which led to vastly greater use of the EVs over the entire service area. Interestingly, TEPCO found that the added charging station was used sparingly (Anegawa (2011); Botsford and Szczepanek (2009)).

PEVs also raise problems related to their interactions with electric power systems. Because electricity demand and supply must be equal at all times, generation, transmission, and distribution capacity are built to serve the system's anticipated peak demand.[1] In most systems this peak is rarely achieved, meaning that if PEV charging is properly timed and coordinated, it can be accommodated without any extra capacity needing to be built. According to the United States Department of Transportation's Federal Highway Administration, Americans drove a total of about 4.76 trillion km in 2011.[2] Assuming a 0.207 kWh/km EV efficiency[3] and 20% total energy losses in transmission, distribution, and EV charging, electrifying the entire vehicle fleet of the United States would have increased average system load by about 139.5 GW. In comparison, the EIA (2012) reports 4105.7 TWh of electricity generation in the United States in 2011, amounting to 468.7 GW of average load. Adding the average load from PEVs would still be well within the 1054.8 GW of installed generation capacity in 2011. Rather than additional average load, however, the impacts of PEVs may most affect the system at the distribution level if charging demand is coincident with peak load. Electricity demand in many power systems peaks on summer afternoons, due to building cooling loads. If PEV owners recharge their vehicles upon arrival home, the added demands could considerably increase these systems' peaks. The risks are exacerbated in residential distribution systems in cases in which the availability of charging stations in offices and public areas is limited Weiller (2011). Using hybrid-electric vehicle adoption to forecast PEV adoption, Mohseni and Stevie (2009) show that significant spatial clustering of PEV owners' residences can occur, which can yield extremely high distribution-level loads. These findings imply that PEV charging will need to be properly timed to use spare system capacity. Achieving this coordination is a non-trivial issue and the extent to which centralized control may be needed is unclear. Without proper coordination, additional system capacity may have to be added.

PEVs may also raise environmental concerns. EPRI (2007a,b) shows that PEVs, even if recharged on the most CO_2-intensive electricity mix, such as in coal-based systems, lead to reduced life-cycle greenhouse gas emissions relative to conventional gasoline or diesel vehicles. Charged on renewable electricity, the tailpipe emissions impacts of PEVs are reduced to zero in terms of greenhouse gases and other pollutants, which are also a concern. For instance, Sioshansi and Denholm (2009) show that PEV use in the state of Texas may result in higher net SO_2 emissions compared to gasoline vehicles due to the high sulfur content of coal used to generate electricity there. The emissions impacts are therefore highly system-specific and highlight the benefits of increasing the integration of renewable generation sources in the electricity mix.

PEVs and renewables have a natural synergy between them that can aid their integration. The environmental benefits of PEVs are best achieved in renewable electricity systems, as described above. The synergy also stems from the fact that successfully integrating renewables into power systems ultimately requires system flexibility which PEVs can provide. This flexibility can come from either the demand- or supply-side. Many power systems today rely on supply-side flexibility that is typically provided by natural gas- and oil-fired and hydroelectric generators. These types of units, which can be switched on and off and have their output ramped up and down quickly, compensate the difference between the system's net load and the output of inflexible baseload generators. The use of these units imposes short- and long-run costs on the system, however. In the short-run, flexible units must be loaded below their maximum output rating, which decreases their operating efficiency. This is demonstrated in Figure 1, which shows the heat rate of a natural gas-fired combined cycle generator as a function of its output. The heat rate, which is inversely

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[1] Due to generator, transmission, and distribution failures, power systems are normally slightly 'oversized' relative to the peak.

[2] These data are available at `http://www.fhwa.dot.gov/policyinformation/travel_monitoring/tvt.cfm`.

[3] This is the tested efficiency of a Nissan Leaf, as reported at `http://www.fueleconomy.gov/feg/evsbs.shtml`.

proportional to efficiency, increases noticeably as the generator is more lightly loaded. In the long-run, a system that relies exclusively on supply-side flexibility must shift the generation mix toward more flexible units, which may have lower operating efficiencies than other technologies.

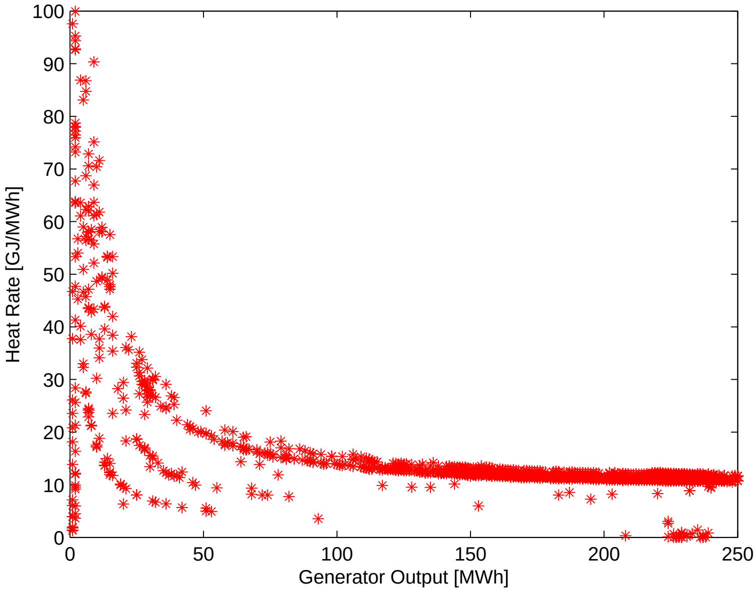

Figure 1: Actual heat rate of a combined-cycle natural gas-fired generator as a function of loading.

PEVs can instead provide low-cost demand-side flexibility. From the perspective of the system operator (SO), PEVs can provide renewable-integration services by having their charging load follow renewable availability, reducing the need for supply-side flexibility. As for consumers, as long as the PEV battery is recharged in time for the next trip, the disutility or cost they might bear from delayed charging may be compensated or managed by attractive contracts. Such contracts already exist for demand response services in some electricity markets, with the long-running air conditioning cycling program operated by Southern California Edison serving as one example (Espinosa (1987)). While this is not necessarily a cost-free flexibility source for the SO, the marginal cost is likely to be lower than currently used alternatives.

PEVs may further be allowed to discharge when grid-connected, also known as providing vehicle-to-grid (V2G) services. These services can lead to even greater renewable-integration benefits. In V2G mode, PEVs can discontinue charging and start discharging their batteries if there is an unexpected renewable generation decrease. A common issue with V2G services, however, is that frequent energy discharge could severely decrease PEV battery life. Providing renewable-integration services or V2G can be beneficial to PEV owners if the value of the service is properly remunerated. Appropriate business models must be designed to distribute the value of the benefits between PEV owners, SOs, and renewable generators, for example by using specialized tariffs for PEVs, time-variant or other dynamic pricing schemes, or other forms of subsidies.

The goal of this article is to further survey the renewable-integration role that PEVs can play and to discuss related implementation issues and questions. The remainder of this article is organized into four sections. Section 2 further details the challenges raised by integrating renewable energy sources into electric power systems while Section 3 discusses the role that PEVs can play in mitigating these issues. Section 4 summarizes some technical and economic implementation issues that may arise. Section 5 concludes.

2. Renewable Integration Challenges

As noted in Section 1, integrating renewable energy sources into electric power systems can raise a number of technical and economic issues. These mainly stem from the variability and uncertainty of the real-time availability of renewables. These characteristics of renewables affect power system operations and planning on a variety of timescales. To better understand these impacts, we first discuss the three main operational planning horizons that are pertinent to renewable integration. We then discuss how renewables affect these planning processes.

2.1. *Power System Operations and Planning Processes*

At one extreme, real-time active and reactive power demand and supply must be in constant balance to ensure that the system's frequency and voltage are within acceptable limits. These types of dynamic stability issues must be studied and managed on the milliseconds to seconds timescale.

The next level of operational planning includes unit commitment, economic dispatch, and optimal power flow analyses. Unit commitment, which may be done on an hour- to week-ahead basis, determines which generators must operate at each time step within the planning horizon to serve forecasted demand at minimum cost. A day-ahead unit commitment that models hour-long time steps is typical, although these details vary among power systems. Once the commitment (on/off status) of each generator is decided by the unit commitment model, each generator's energy production must be determined. This is done in an economic dispatch model and the resulting power flows on the transmission network elements are modeled to ensure that they are within the physical limits of the system. This dispatch process can be done hour-ahead. In many systems the dispatch is also recomputed in a rolling fashion every five to 15 minutes, using the most recently available system information.

The real-time dynamic stability, unit commitment, and intraday economic dispatch processes have a hierarchical interdependency among them. For instance, a unit commitment model typically has a simplified power flow model embedded in it to ensure that the system can be feasibly dispatched in real-time without violating transmission constraints. The unit commitment model also includes reserve requirements that ensure that the generators committed in each time step have sufficient excess capacity and ramping capability to serve load under a variety of unanticipated contingencies. Traditionally, generator or transmission failures or unanticipated load increases are the types of contingencies considered. There is a further interdependency between these operational planning stages and system dynamic stability: generator commitments and dispatch must provide sufficient supply-side flexibility to maintain the system's frequency and voltage within acceptable tolerances. These requirements are modeled by including constraints in the operational models requiring that the generators committed be able to provide higher-quality reserves with extremely fast response times. Sheble and Fahd (1994) provide a survey of the unit commitment and related literature.

The final level of planning is long-term generation and transmission investments and retirements. Due to the potentially long lead times involved, investment decisions may be made a decade or longer in advance of project completion. Although generation and transmission construction can be time-consuming, delays associated with regulatory approval, financing, and local opposition to a project can account for the bulk of this lead time. As with the unit commitment process, there is a hierarchical interdependency in this long-term planning. This is because investments must be made while anticipating future electricity demands and how those demands will be served by the generation and transmission assets installed in the system. Thus, investment planning should ideally include unit commitment, dispatch, and power flow and dynamic stability analyses. In practice, simpler heuristics based on load-duration curves and the capital and operating costs of different generation technologies are often used to capture unit commitment and dispatch costs (Stoft (2002)). These heuristics may also be supplemented with reliability models, which determine how much excess capacity should be installed to reliably serve load in the face of generator and transmission failures (Billinton and Allan (1984)).

2.2. *Effects of Renewables on Power System Operations and Planning*

Integrating renewable energy sources into electric power systems can further complicate these operation and planning processes. Maintaining real-time energy supply and demand balance and system stability can be more difficult, since renewables increase supply-side variability. Similarly, SOs must account for renewable variability when making unit commitment and economic dispatch decisions. Since it can take hours to startup some generators,[4] the set of generators that is committed must have sufficient excess capacity and ramping capability to respond to unexpected reductions or increases in renewable availability. In some systems this flexibility is ensured by adjusting reserve requirements in the operational planning models, whereas others have introduced new reserve or flexibility products. For instance, Abdul-Rahman et al. (2012) discuss the introduction of a flexi-ramp constraint in the California ISO's operational planning process and Wang and Hobbs (2014) compare the operational benefits of this constraint to other renewable planning mechanisms. This constraint, which was originally only enforced in the real-time dispatch, ensures that the generators committed have sufficient ramping capability to cover anticipated supply differences between the five- and 15-minute-ahead dispatch processes. Once this constraint was incorporated into real-time operations, the California ISO proposed adding it to the day-ahead unit commitment as well. In addition to planning difficulties, these operational changes also have economic implications. As noted in Section 1, some sources of flexibility impose added costs on the system. Many power systems today rely almost exclusively on flexible natural gas- and oil-fired generators to balance renewable variability. As Figure 1 illustrates, this can reduce the efficiency and increase the operating cost of these generators.

Renewables also affect long-term generation and transmission investment. Generation investment is affected in two important ways. One is that long-term generation investments must account for the limited ability of variable renewables to reliably serve load. A number of studies, which Keane et al. (2011) survey, estimate the contribution of wind toward reliably serving load in a variety of systems. These analyses find that the marginal capacity value[5] of the first increment of wind tends to range between 15% and 50% of the nameplate capacity of the wind plant. Wind's marginal capacity value drops quickly as more is added to the system, however. Analyses of solar conducted by Madaeni et al. (2012, 2013); Pelland and Abboud (2008); Perez et al. (2006, 1993); Xcel (2009) show higher capacity values than wind, due to greater coincidence between solar availability and electricity demand in many power systems. Underestimating the capacity contribution of renewables can result in higher ratepayer costs, since excess generating capacity must be built. Conversely, overestimating their capacity contribution reduces system reliability, since insufficient dispatchable generation will be built. In addition to their reliability impacts, renewables may also skew the mix of generators installed. This effect depends on how renewable variability and uncertainty are accommodated in the day-ahead and real-time operational horizons. A system that relies exclusively on flexible conventional generators to accommodate renewables would need to install more generators with such capabilities as the penetration of renewables increases. As an example of this, DeMeo et al. (2005) note the plans of a major manufacturer to introduce a gas turbine product specifically designed to provide such flexibilities.

Renewable integration can also necessitate major investments in transmission facilities. This is because the richest renewable resources in many parts of the world are far from population centers where electricity demand is highest. As an example of this, Mai et al. (2012) model the generation and transmission expansion needed to achieve a power system across the United States that serves between 30% and 90% of electricity demand using renewables. This analysis estimates between 10 million and 200 million MW-miles of transmission capacity being needed to deliver this amount of renewable energy to end customers. The latter case represents a doubling of the approximately 200 million MW-miles of existing transmission capacity.

2.3. Summary

In summary, integrating renewable energy sources in electricity systems poses a number of challenges for real-time and short- and long-term system planning due to their variability and uncertainty. Renewables increase the challenges of maintaining dynamic stability—frequency and voltage—in power systems due to the effect of sudden unplanned increases or shortages of generation. In (day-ahead) unit commitment and

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[4] Generator startup times are technology-dependent. For instance, an oil- or natural gas-fired combustion turbine can be started up within minutes whereas steam turbines may take the better part of a day.

[5] Capacity value is a standard metric used to estimate a resource's contribution to system reliability. Roughly speaking, a generator's capacity value measures how much load can be added to the system (when the generator is also added) without changing system reliability.

(intraday) economic dispatch and power flow models, renewables introduce a degree of uncertainty that must be mitigated with flexible generators, usually fossil-fueled, causing high ramping costs and efficiency losses due to part-load operation, as illustrated in Figure 1. Renewables further raise challenges for long term investments due to the difficulty of making reliable capacity and generation forecasts, as well as the costs of transmission capacity expansion. However, the simultaneous integration of PEVs along with renewables in electric power systems can mitigate some of these effects and lead to additional synergistic benefits. These are discussed in the following section.

3. Renewable Integration Benefits of PEVs

3.1. Type of Services

In terms of impacts on electric power systems, PEV charging not only increases energy and power demand, calling for new capacity investments, but can also lead to synergies with renewable energy and improve the utilization of assets in the electric power system (Sioshansi and Denholm (2009)). If PEVs are scheduled to recharge when system demand is lowest, they can improve the overall capacity utilization factor of the electric power system and generate cost savings for the user and the system (Denholm and Short (2006); Sheikhi et al. (2013)).

PEVs broadly provide two types of services that can benefit electric power systems with renewable energy generation: passive services, wherein the PEV is used as a load with optimizable consumption, or active services, which rely on bidirectional power flow between the vehicle and the charger. In the latter case the PEV provides power back to the grid. These services can resolve some of the problems of integrating renewables on the time scales discussed in Section 2: real time demand and supply balancing, unit commitment, and long-term system planning.

3.2. Real-Time, Demand-Side Source of Flexibility

For real-time power system operations, PEVs are a flexible load that can be switched on and off nearly instantaneously to respond to the variability of renewable generation. A PEV fleet represents an attractive demand-side resource to respond to unplanned excess or under-supply of variable renewable energy on the intraday and real-time markets. Grid-connected PEVs are loads that typically consume between 2 kW and 50 kW but can consume more than 100 kW of power at fast-charging stations (*e.g.*, Tesla ‘superchargers’). If adequately managed through charging schedulers, shifting this load can present significant benefits in a power system with renewables.

Part of the value of this demand-side flexibility is the avoided costs of ramping up and down the least-flexible power plants in the system and the avoided requirements from flexible supply-side balancing resources (such as natural gas- and oil-fired plants). PEVs can provide frequency regulation and short-term response, *i.e.*, reserve power that responds within 30 seconds to changes in supply and demand imbalances.

Renewable generators and SOs bear the costs of real-time system imbalances due to renewable variability, either through the lost revenue of curtailed energy when the system is long or through the cost of procuring reserve energy on the intraday or real-time market when the system is short. PEVs can alleviate these costs by switching on to charge when renewable production is in excess of system demand. The mean absolute error of wind power forecasting four to 24 hours ahead is estimated to be about 10% in the United Kingdom, with similar forecasting errors observed in other systems. This represents significant value as lost revenue or added costs for generators and SOs. An analysis of the UK market by Newbery (2012) shows that the system is long about 70% of the time, suggesting that PEVs could provide most of their value as flexible loads that avoid curtailed renewable energy.

In times when the system is short, however, for example due to less renewable generation than expected, PEVs could reduce the system load by interrupting their charging, thus avoiding the costs of energy procurement on the intraday and real-time reserve (or balancing) markets. Conceivably, PEVs could actively participate in power systems in order of priority rankings for vehicle charging assigned according to stated user preferences based on the state-of-charge and the planned or expected travel schedule of the vehicle. Some of the practical implementation issues are discussed further in Section 4. Xi et al. (2014) analyze historical reserve prices, showing that they are typically highest when the market is short. In addition to the value of reducing demand in short systems, PEVs could provide value as power sources as well. Their value as supply-side resources is discussed in greater detail in the following section.

3.3. Real-Time, Supply-Side and Storage Resource

If bidirectional power transmission is implemented between PEVs and the grid through chargers, PEV batteries offer additional opportunities as energy storage units that can charge and discharge energy as required by the system. One of the fundamental properties of electricity markets is that electricity cannot be stored, *i.e.*, it is currently uneconomical to integrate dedicated storage devices in electricity systems (Sioshansi et al. (2012)). However, as the integration of uncertain renewable energy picks up scale, grid-scale storage will become increasingly valuable to manage the resulting supply volatility (Bathurst and Strbac (2003); Denholm et al. (2010)).

PEVs can add a time-dimensional buffer to power system operations. PEVs represent a valuable storage and supply resource both at the grid level, if entire fleets of thousands to millions of vehicles can be managed at once, and at the level of individual homes. As supply-side resources, fleets of PEVs can store excess renewable energy as it becomes available and release it at a later time when required by the system. At a more local level, if combined with individual home or building renewable energy sources, PEVs can provide similar opportunities to optimize the owner's energy consumption and generation through their storage capacity (Antunes et al. (2013); Balta-Ozkan et al. (2013)). PEVs are interesting components of 'smart' home and building energy management systems. These services are usually referred to as V2G, 'vehicle-to-home' (V2H), and more generally 'vehicle-to-X' (V2X) (Lund and Kempton (2008); Tuttle and Baldick (2012)). The compensation and incentive mechanisms for PEV owners to participate in the provision of such services are discussed in Section 4.

PEVs as supply-side resources are particularly valuable due to their low opportunity cost. Because their primary purpose is their use for driving, consumers would invest in them (as cars) regardless of their use as grid resources. Indeed, Sioshansi and Denholm (2010) argue that if PEV owners are properly compensated, their use as grid resources provides an added incentive for their adoption. As opposed to other solutions such as pumped hydroelectric storage, hydrogen-based power-to-gas storage, compressed air energy storage, or sodium-sulfur batteries, there is no added investment cost in using PEVs as supply-side and storage resources. There are, however, variable costs associated with the use of PEVs for grid services, due to the (currently uncertain) degradation of the battery that results from increasing the number of charge/discharge cycles (Sioshansi and Denholm (2010)).

In summary, similarly to other types of electricity storage, PEVs reduce required investments in reserve generation capacity to maintain the reliability margin and manage the variability of renewable energy. As discussed in Section 2, much of this flexibility is currently provided by natural gas-fired plants, which will require further investments as more flexibility is needed. The storage capacity of PEVs can also help alleviate congested transmission lines (Sioshansi et al. (2009)), thus avoiding the cost of reinforcing transmission. The avoided costs of ramping conventional power plants up and down to manage renewable variability is also a benefit of PEVs. In addition to these avoided costs, PEVs provide the opportunity to arbitrage electricity prices through smart scheduling of demand (charge), storage, and supply (discharge). The viability of using PEVs for grid or home-based energy services depends on the volatility and magnitude of electricity prices in the electricity market (Moreno et al. (2012)).

3.4. Strategic and Long-Term Benefits in the Transition to a Renewable, 'Smart'-Enabled Power System

Benefits from PEVs for renewable integration include multiple less direct sources of economic value. SOs and utilities also avoid the research and development costs of battery storage technologies if other companies, *i.e.*, battery manufacturers and/or auto manufacturers (OEMs), invest in battery technologies for vehicles. Clearly, these other types of companies will be motivated to invest in batteries to sell vehicles and batteries to the PEV and other markets. Section 4 further discusses the distribution of revenues and costs amongst industry participants and PEV owners.

PEVs are part of a synergistic transition to 'smart' information and communication technology (ICT) in the electric power sector—they offer an additional reason to introduce smart meters and emphasize the value proposition of smart energy management by consumers. Individual consumers who have their own renewable energy generation units, such as solar panels in their homes, and a PEV, have all the more reason to use their smart meters to manage and optimize their consumption, generation, and storage capacity.

PEVs may be increasingly committed as power sources in energy markets when their sales penetration makes them available by millions. Until then, individual battery capacities of mid-sized PEVs, which range between around 20 kWh and 85 kWh, will not be significant enough to moderate renewable energy generation on the wholesale level. For PEV applications to be viable at the wholesale level, capacities of at least 1 MW to 2 MW would have to be traded in each V2G transaction, *i.e.*, roughly the equivalent of 500 EVs connected to a standard 3.7 kW European circuit. Taking into account the availability factor of the vehicles, the number of EVs on the road in a given electricity control area would therefore have to be considerably higher than this value.

As the scale of the PEV market increases, two other major benefits of deploying them in the context of renewable energy systems will also materialize. The first is, of course, the benefits of emissions reductions in the transport sector—charging PEVs from renewable electricity leads to emissions reductions, and the reductions are directly related to the simultaneous growth in both renewables and PEV markets. The second advantage is related to the deployment of associated technologies, such as the smart energy management systems mentioned above. As PEV adoption increases, industry players will develop systems and features that will increase the possibilities to use them as resources, as discussed in the previous two sections. ICT companies appear to be waiting for more certainty in the PEV market before developing the architecture that would be needed to realize new business models such as V2H.[6] Until then, the opportunities will remain minimal and PEVs will be integrated in electric power systems as ordinary loads, the charging of which is managed on an individual basis.

4. Implementation Issues

4.1. Consumer Incentives

The first issue to consider in the implementation of PEV services for renewables integration is whether consumers would accept ceding control of their vehicles to third parties, *i.e.*, SOs or charging managers, and whether they would be willing to change their charging behavior to provide such services. Similarly to other demand response mechanisms, PEVs could be controlled either directly by the SO or incentivized by price signals to the consumer (Espinosa (1987)). Price signals are a simple form of incentive as the user remains in control of the vehicle—however, the benefits of the services described above are less likely to be realized if they are left up to the consumer. This is because of difficulties in structuring dynamic prices that achieve socially optimal charging behavior in a decentralized manner (Xi and Sioshansi (2014)).

Clearly the acceptance of third-party PEV control depends on the level of incentives that are provided and on the level of control over the vehicle that is ceded. To the first point, the maximum amount that a PEV owner could expect to be compensated for the service provided is the total value to the power system of the services from the charge time shifting and/or power supply that it provides. The minimum value could be zero, in the case where providing the service does not impinge in any way on the convenience the PEV owner derives from the vehicle. In this latter case, the user would have to agree to participate out of pure volunteer interest. A number of compensation methods can be designed depending on the client and the service provided. It may be impossible to price the services on a per-transaction basis due to the complexity of calculating the exact value saved by shifting PEV load or the provision of short-term reserve energy. Such a calculation is further complicated since the realized electricity prices would not be exogenous but would depend on the services provided. Fixed fee-based pricing thus appears to be a reasonable solution (Caillaud and Jullien (2003)). Contracts for PEV charging could include varying levels of discounts according to how flexible drivers are in allowing vehicle charging interruptions. The willingness-to-accept for different cases should be the subject of further research.

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[6] This is based on interviews with utility and ICT solutions providers in Japan, April 2013.

4.2. Business Models

Business models describe the value proposition and the structure of relationships that enable an organization or a network of organizations to create and capture value around a new business opportunity (Zott and Amit (2010)). PEVs suffer from a lack of an attractive value proposition for buyers, as noted in Section 1, because of high upfront costs due to the battery component and the phenomenon of 'range anxiety' due to the combination of limited vehicle range and the scarcity of available charging infrastructure. Redefining the business model for PEVs by accounting for their value as electricity system resources may offer considerable advantages for all parties involved. Here we discuss the responsibilities of OEMs, battery owners and manufacturers, grid operators, utilities, and aggregators around PEV services for renewables.

As discussed in Section 3, the benefits of using PEV batteries to manage renewable electricity variability and uncertainty in real-time markets are captured mainly by the generators that avoid the opportunity cost of curtailment and entities that avoid the cost of reserve power procurement. The allocation of the latter cost varies from one market to another, but it is often borne by renewable generators or socialized to loads. In traditional vehicle sales business models, OEMs and battery manufacturers bear the costs of developing and producing the batteries, while consumers bear the full costs of buying the vehicle and the battery. Clearly, a redistribution of the costs and value capture from PEV applications for renewables is necessary so that part of the benefit received by SOs and renewable generators is given either directly to OEMs and battery manufacturers, in a direct contractual relationship that bypasses the consumer, or back to the consumer. The difference between the two cases would be the ownership of the battery. In a case in which consumers lease the battery from the OEM, which retains it as an asset, new partnerships between OEMs and SOs or generators may arise, allowing the OEM to recuperate the value provided to the power system or renewable generator through the PEV Weiller et al. (2015).

Furthermore, the entry of an aggregating agent specialized in PEV management would be necessary to realize the services described, as is discussed by Bessa and Matos (2012); Quinn et al. (2010). The PEV aggregator would be responsible for the optimization and management service to consumers and allow for the implementation of the services across multiple, not just individual, PEVs. Bessa and Matos (2012); Hota et al. (2014); Kley et al. (2011); San Román et al. (2011); Tuttle and Baldick (2012) review opportunities and relationships between existing and new agents in electric power systems that include renewable energy and PEVs. Tuttle and Baldick (2012) offer an evolutionary roadmap of PEV and grid interactions, including an understanding of the implications of the various energy service business models in terms of communications architectures, legal responsibilities, and revenue structure.

Table 1 summarizes the distribution of revenues and value suggested in this paper from using PEVs as resources for renewable energy integration across different players in the value chain.

4.3. Charging and Communications Infrastructure

The implementation of services for renewable integration from PEVs requires new ICT infrastructure that links the vehicle, the charger/home, and the SO. Currently, direct communication between vehicles and SOs is technically feasible, as evidenced by recently developed standards such as IEC 618511. However, legal control and ownership issues represent important barriers that prevent the implementation of the business models described in this article. Regulation has to address the limits and control rights for the different actors. Cars are usually manufactured as 'closed systems' where the software and communications network are contained exclusively within the vehicle and are proprietary to each OEM Weiller and Neely (2014)—this is likely to cause issues with the implementation of the business models discussed in Section 4.2. Also, as noted in Section 3.4, as long as the PEV market remains in the early-adopter stage, there is no justification for companies to design a new platform specifically for PEVs Weiller and Neely (2014).

4.4. Battery Ownership and Warranty

As mentioned in Section 3, making a PEV battery available for renewable energy balancing services may result in faster degradation of its cycle-life. If a user enters a contract agreement for V2G with an electricity supplier, the OEM warranty on the PEV battery may be restricted or voided. This issue must be resolved before the PEV services for renewable integration can be implemented. We discuss some possible

Table 1: Business models for PEV-renewables integration.

Functionality	Main Beneficiaries	Main Sources of Value	Service Provider(s)	Cost Distribution
Passive (Unidirectional): Charge Scheduling	1. Users 2. Renewable generators	1. Lower electricity prices 2. Flexible load guaranteeing uptake	Charge manager	Battery owner (OEM or consumer)
Semi-Passive/Active: Storage	1. Users 2. SO 3. Renewable generators	1. Avoided investment in other storage technology 2. Avoided curtailment 3. Lower electricity prices	Aggregator	1. Battery owner: Consumer or utility/SO 2. Reallocation of value from utility/SO to battery owner
Active (Bidirectional): Power Supply	1. Users 2. SO 3. Renewable generators	1. Avoided curtailment 2. Avoided cost of balancing/reserve energy 3. Zero cost of electricity consumed (self-supply)	Aggregator	1. Battery owner: Consumer or utility/SO 2. Reallocation of value from utility/SO to consumer

mechanisms to overcome this barrier in Section 4.2, such as having the OEM maintain ownership of the battery, which is leased to the consumer. In this case, the OEM would directly enter into a contractual arrangement with the SO to provide renewable integration services.

4.5. Summary

In summary, PEVs offer benefits for renewables integration due to their flexibility as resources from a demand perspective. They are loads that draw significant amounts of power from the grid, yet can be interrupted to meet system requests when recharging is not a high priority, *i.e.*, necessary to accomplish an imminent trip. The low switching (ramping) costs of PEVs are advantageous to respond to unplanned variations in renewable energy output, thus helping with some of the real-time stability management and short term unit commitment and dispatch issues in electric power systems. In addition to demand-side benefits, a PEV battery can be used as an electricity storage unit, effectively providing a 'buffer' against the uncertainty and variability of renewable energy. Furthermore, if PEVs are enhanced with V2X functionalities, *i.e.*, the ability to supply power back to the grid, the home, or any other load, the renewable-integration benefits can be increased. The use of PEVs as supply-side resources is likely to reduce the investment costs required in other flexible power plants to accommodate renewables.

We noted, however, that these benefits depend on the scale of PEV adoption. Given the significant infrastructure investments and societal and behavioral changes required for these synergistic benefits to materialize at a scale useful for electric power systems, much higher adoption rates of PEVs than currently observed would be needed. Innovative business models around PEVs that allow OEMs and electricity suppliers to capitalize on the synergy with renewables have been briefly discussed to solve some of the challenges to PEV market growth.

5. Concluding Remarks

This article discusses two technology options, renewable electricity generation and the electrification of transportation, that are being promoted by policy makers and industry players to achieve two of the greatest objectives of this century: meeting growing global energy demand while reducing greenhouse gas emissions. Addressing both objectives implies shifting part of this energy demand away from fossil fuels to other primary energy sources. The adoption of both renewables and plug-in electric vehicles has been hindered by significant challenges despite their known potential to improve energy sustainability in electric power systems and transportation—two sectors which together account for nearly 60% of energy consumption globally.

In Sections 1 and 2, we discuss the challenges created by the integration of renewables due to the uncertainty and variability of generation at multiple timeframes of electricity system planning, from real-time demand and supply balancing to long term investments. The adoption of PEVs, on the other hand, is currently challenged by high purchase costs and limited range and charging infrastructure.

In Section 3, we discuss the extent to which the challenges of renewable integration can be addressed by PEVs, which in turn benefit from synergies with renewables. The aggregate capacity of grid-connected PEV batteries can be ramped up or down quickly and at a lower cost than the flexible generators traditionally used to manage renewable variability. PEVs offer potential for electricity storage, as well as supply and load flexibility that can help deal with the challenges of renewable integration on very short (real-time) and short (day-ahead) system operations and planning. In the long run, PEVs provide significant benefits towards supporting renewables integration and associated emissions reductions through the avoided costs of installing and operating alternative flexible conventional generators. PEVs also avoid the costs of investments in other grid storage technologies. At the scale of individual households, PEVs provide clear synergistic advantages for the growing market of end-users who own renewable micro-generation assets such as rooftop solar panels. Providing direct financial benefits to consumers, PEVs can thus support renewable penetration without the need for centralized investment.

Conversely, we conclude that the integration of renewables can contribute to supporting the growth of the PEV market, which has been slow relative to policy targets and industry expectations. The co-deployment of renewables and PEVs is leading to new business models to redistribute the value of the most expensive component of the vehicle, the battery, between OEMs, utilities, and consumers. We suggest that distribution system operators and electricity supply companies have an incentive to support part of the investment in PEV battery research and development and commercialization given their shared interest in PEVs growing to a significant share of the automobile fleet. We highlight some of the challenges with implementing renewables/PEV systems to capture value from their synergies. New communication and control infrastructure must be deployed between vehicles and the grid—requiring consumer participation and potentially new regulation in electricity markets. Strategic cooperation between the various industry players is also expected to remain a significant challenge and barrier to the deployment of joint business models. A suggested next step for future research is to explore the deployment of innovative business models to enable the growth of the PEV market and to support renewable energy integration.

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