ANNUAL REVIEWS

Annual Review of Environment and Resources

The Future Promise of Vehicle-to-Grid (V2G) Integration: A Sociotechnical Review and Research Agenda

Benjamin K. Sovacool,[1,2] Jonn Axsen,[3] and Willett Kempton[4]

[1]Department of Business Development and Technology, Danish Center for Energy Technology, Aarhus University, 7400 Herning, Denmark; email: benjaminso@auhe.au.dk

[2]Science Policy Research Unit, University of Sussex, Brighton BN1 9RH, United Kingdom

[3]School of Resource and Environmental Management, Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada

[4]College of Earth, Ocean, and Environment, University of Delaware, Newark, Delaware 19716

Annu. Rev. Environ. Resour. 2017. 42:377–406

First published online as a Review in Advance on July 27, 2017

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-030117-020220

Keywords

mobility, transportation, decarbonization pathways, electric mobility, vehicle-to-grid (V2G), vehicle grid integration (VGI)

Abstract

Vehicle-grid integration (VGI) describes various approaches to link the electric power system and the transportation system in ways that may benefit both. VGI includes systems that treat plug-in electric vehicles (PEVs) as controllable load with a unidirectional flow of electricity, such as "smart" or "controlled" charging or time-of-use (TOU) pricing. VGI typically encompasses vehicle-to-grid (V2G), a more technically advanced vision with bidirectional flow of electricity between the vehicle and power grid, in effect treating the PEV as a storage device. Such VGI systems could help decarbonize transportation, support load balancing, integrate renewable energy into the grid, increase revenues for electricity companies, and create new revenue streams for automobile owners. This review introduces various aspects and visions of VGI based on a comprehensive review. In doing so, it identifies the possible benefits, opportunities, and barriers relating to V2G, according to technical, financial, socio-environmental, and behavioral components. After summarizing our sociotechnical approach and the various opportunities and barriers indicated by existing literature, we construct a proposed research agenda to provide insights into previously understudied and unstudied research objectives. We find that the majority of VGI studies to date focus on technical aspects of VGI, notably on the potential of V2G systems to facilitate load balancing or to minimize electricity costs, in some cases including environmental goals as constraints. Only a few studies directly investigate the role of consumer acceptance and driver behavior within such systems, and barely any studies address the need for institutional capacity and cross-sectoral policy coordination. These gaps create promising opportunities for future research.

Contents

1. INTRODUCTION

Globally, the transportation sector is rife with market failures—notably its continued reliance on fossil fuels for 95% of its energy and the resulting consequences for climate change, air pollution, and other negative social impacts. Many researchers, policymakers, and other stakeholders therefore view a widespread transition to electric mobility as both feasible and socially desirable. Electric mobility includes both plug-in hybrid vehicles (PHEVs) that are fueled by both gasoline and grid-provided electricity, and battery electric vehicles (BEVs), fueled only by electricity.

We refer to both types collectively as plug-in electric vehicles (PEVs). From the climate change mitigation perspective, the International Energy Agency suggests that PEVs must make up at least 40% of new vehicle sales globally by 2040 to be on track to stabilize greenhouse gas (GHG) concentrations at 450 ppm (1). Others similarly argue that penetration in that approximate range is necessary to achieve deep climate mitigation targets by 2050 (2).

Significant adoption of PEVs in any region will inevitably impact the electricity grid due to increased electricity demand and the temporal shifting of demand peaks—offering both benefits and risks to electricity systems. Over the past two decades, researchers have explored various notions of what is alternatively called vehicle-to-grid (V2G) (3), grid-integrated vehicles (GIVs) (4), or vehicle-grid-integration (VGI). These overlapping concepts describe efforts to link transportation and electricity systems in ways that may provide benefits to both, and some policymakers are beginning to recognize this potential (5). VGI is proposed as an overarching term, which includes systems that treat PEVs as controllable loads with a unidirectional flow of electricity, through mechanisms such as time-of-use electricity pricing or control of charging by a central entity (e.g., utility-controlled charging). VGI also includes the more technically advanced idea of V2G, which involves a bidirectional flow of electricity between the PEV and electrical grid, adding the ability for idle PEVs to store electricity from the grid and to give or sell it back at desirable times. Essentially, a V2G configuration means that personal automobiles have the opportunity to become not only vehicles, but mobile, self-contained resources that can manage power flow and displace the need for electric utility infrastructure. They operate as vehicles when drivers need them but switch to power sources during peak hours, recharging at off-peak hours such as later at night (6).

PHEV: plug-in hybrid electric vehicle

BEV: battery electric vehicle

Plug-in electric vehicle (PEV): includes both battery electric vehicles and plug-in hybrid electric vehicles

GHG: greenhouse gas

V2G: vehicle-to-grid

GIV: grid-integrated vehicle

VGI: vehicle-grid integration

In effect, the various forms of VGI can be designed to offer benefits to a variety of stakeholders. For electric utilities, VGI can provide back-up power, support load balancing, reduce peak loads (7, 8), reduce the uncertainty in forecasts of daily and hourly electrical load (9), and allow greater utilization of existing generation capacity (10, 11) and of distribution infrastructure (12). For governments seeking to slash GHG emissions, VGI can help integrate intermittent renewable electricity generation into the grid (13) by using renewable energy when it is available (14, 15), on top of the GHG benefits of electrifying vehicles. If the value created by VGI is used to incentivize PEV ownership, it could further reduce GHG emissions in the transportation sector (16, 17). In turn, VGI systems could also benefit PEV buyers, electricity rate payers, and society more generally.

In this review, we begin with a brief summary of electric mobility and VGI systems before moving to present and define our sociotechnical perspective. The review then focuses on the future promise of VGI, namely emphasizing its technical potential to improve the electric utility grid alongside financial, social, environmental, and consumer benefits. We counterbalance this discussion of benefits with one of challenges and barriers, including technical issues such as communication and control, financial hurdles, negative environmental externalities, and a range of likely behavioral obstacles among users. We conclude by identifying research gaps and presenting a critical research agenda with insights and conclusions for energy and environmental scholars more generally.

To review and synthesize the latest research and thinking on opportunities and barriers to VGI, this article takes a sociotechnical approach. In contrast, much state-of-the-art literature on VGI follows a technical or techno-economic perspective. Technical research is conducted primarily by engineers and natural scientists and tends to focus on the optimal technical characteristics of VGI systems, such as needed improvements in batteries, electrical grid infrastructure, and information and communication systems (6). This perspective leads research managers (in government and in corporations) to pursue research activities in computing and processing, power electronics, low-cost and lightweight materials, and grid interaction. They have laid out a research program aimed at, for example, improving the conductivity and mechanical strength of batteries. The techno-economic perspective adds to this a limited economic component, which is the financial costs of the systems, typically seeking to optimize a VGI system from a financial cost-benefit analysis perspective.

HEV: hybrid electric vehicle

EVSE: electric vehicle supply equipment

AC: alternating current

DC: direct current

In contrast, a sociotechnical perspective, as the name suggests, not only includes technical and financial components, but also extends analysis to economics, politics, social values, and business models. This approach suggests that infrastructure and new technologies weave together pieces of hardware, organizations, institutional rule systems and structures, and cultural values (18). Viewed as a device, an automobile is just a box with an engine and wheels, but as a system, it includes roads, fuel stations and refineries, the maintenance industry, registration offices, insurance companies, business models and legal frameworks for use and charging of electric cars (19).

2. BACKGROUND: ELECTRIC MOBILITY AND VGI

2.1. PEV Technology and Charging

Most modern automobiles employ internal combustion engines, which start quickly and provide power as soon as drivers need it. By contrast, hybrid electric vehicles (HEVs), which have seen commercial success for more than 15 years, include a battery and electric motor for a car that uses an internal combustion engine. HEVs use the electric motor and electronics to more efficiently operate the internal combustion engine, which can cut fossil fuel usage, GHG emissions and air pollution. HEVs do not plug into the electrical grid, whereas two types of PEVs do. First, PHEVs are capable of recharging from the electrical grid, while maintaining an internal combustion engine. Second, BEVs draw their energy for propulsion strictly from a battery. Although several consumer-based studies point out that there is greater mainstream market potential for PHEVs, at least in North America (20–22), the limited sales volume of BEVs to date has been higher than sales of PHEVs globally [likely due in part to supply constraints (23)], with an approximately even split in North America (24).

When discussing electric mobility and VGI transitions, it is also important to distinguish the type of vehicle ownership and users in question. For the most part, VGI literature to date has focused on privately owned, light-duty passenger vehicles, including passenger cars and trucks. Alternative fuel research in general tends to neglect fleet operators as well as the freight sector, which largely consists of medium-duty and heavy-duty trucks. However, different vehicle types, user groups, and transportation patterns present different opportunities and drawbacks for PEV technology and VGI. For example, some research suggests that fleet operations may present a particularly strong economic case for VGI (25, 26). Similarly, car-sharing programs may present unique opportunities for VGI (27, 28).

The deployment of PEVs and VGI systems is particularly linked to recharge access, that is, the PEV driver's access to technology that charges PEVs with grid electricity (see the sidebar Charging Stations and Terms for more on charging terminology). Technically, these devices are called electric vehicle supply equipment (EVSE) rather than chargers [because "chargers" convert alternating current (AC) to direct current (DC), whereas EVSEs for AC-charged vehicles do not)]—however, in this article, we use the more colloquial term charger or charging station. PEV drivers can potentially recharge at home, work, or other nonhome destinations such as shopping malls (often called public charging; although, this category typically includes privately owned charging stations that are nonhome and nonworkplace). PEV chargers also vary by the rate at which electricity can be put into the PEV battery, measured in kW.

CHARGING STATIONS AND TERMS

In North America only, an unfortunate nomenclature has been adopted in generic descriptions of charging stations, using the three terms Level 1, Level 2, and Fast DC. A more intuitive and driver-useful description of charging stations is used worldwide (outside North America), and also used in North America "on the ground," that is, in charging station directories and mobile applications that drivers actually use. That classification is simply to name the connector type and optionally the recharge speed [using a power or kilowatt (kW) rating]. This is far more driver-usable because the connector type tells the driver whether or not they can plug their car into that charging station, and the recharge kW tells them how quickly the charging station fills the battery. (More precisely, the recharge speed is the minimum of the charging station's kW provision and the car's kW acceptance—for safety, modern EVSE/PEV systems negotiate to draw power at the minimum capability between the two.)

Standard connectors are the Type 1 (in the United States and Japan, called J1772); Type 2 (rest of world); and, for direct current (DC) charging, one of CHAdeMO, "Combo" or Combined Charging System. Additionally, there is the single-vendor connector made by Tesla, named lucidly but uncreatively the Tesla connector. In-cord chargers are typically 1 to 3 kW, Type 1 charging stations typically 3 to 19 kW, Type 2 typically 22 to 120 kW, and the three DC charging stations range from 20 to 150 kW (29). The number of kilowatt hours added during charging is the kW of the charger multiplied by the hours of charging—for example, to add 20 kWh to a battery (mostly filling a 2016 Leaf battery) would require 10 hours on a 2 kW in-line charger, or 25 minutes on a 50 kW charging station. Because charging speed slows down as the battery fills, time to fill is often cited as the time to fill up to 80% or 90%, and manually unplugging at 80–90% is a good strategy for faster recharge on long trips. The principle is the same: The amount of kWh to put in the battery divided by the kW of the charger is the number of hours it will take. In short, higher kW equals less time to wait.

2.2. VGI Concepts

As noted, VGI is a broad concept that describes efforts to intelligently link vehicles with the electric power grid (5). California's Independent System Operator, which created this term, provides several categorizations of the potential for VGI, where systems can vary by three attributes: (*a*) whether benefits to the grid are provided by individual or aggregated resources, (*b*) whether actors have unified or fragmented objectives, and (*c*) the direction of power flow (unidirectional or bidirectional) (5; see also **Table 1**). First, aggregation refers to whether the PEVs involved in VGI are in a single location or are distributed across a variety of locations (30). Second, the actors

Table 1 Key vehicle-grid-integration concepts and attributes[a]

VGI concept	Attributes
Power flow direction	Unidirectional: V1G, smart charging, controlled charging Bidirectional: V2G
Aggregation of resources	Individual: one resource or multiple resources in one location Aggregated: multiple resources in multiple locations
Actor objectives	Unified: one actor or multiple actors with aligned objectives Fragmented: multiple actors with varying or conflicting objectives
Mechanism of actor engagement	Time-of-use pricing Revenue sharing Education or voluntarism

Abbreviations: VGI, vehicle-grid integration; V2G, vehicle-to-grid.
[a]Table modified from Reference 30.

involved in VGI can be "unified," meaning that the PEV drivers or operators are part of the same entity that is managing the charging for the electric utility or are "fragmented" if different entities, including non-utilities and new market entrants, are involved who might experience different costs and benefits. A VGI system is likely to be simpler to operate with a unified, individual resource, such as a PEV-fleet that has managed charging at one location owned by the fleet operator. Conversely, VGI systems are more complicated if they involve the aggregation of PEV users with fragmented objectives, e.g., PEV-owning households spread across a given region.

In this review, we put more emphasis on the third distinction of direction of flow. Unidirectional flow—also called managed charging, V1G, or smart charging—requires added controls but little change to the charger itself. Managed charging may either control the rate of charging or switch charging on or off. Bidirectional flow, called V2G [first proposed by Kempton & Letendre (7)], allows the PEV to both draw electricity from and provide electricity to the electricity grid, and it needs a charger that requires more design analysis but typically little additional cost. Either managed charging or V2G can provide value to the grid, although one older modeling effort suggests that V2G can be 13 times more valuable, if participating in electricity markets (31). To date, most VGI literature has focused on the V2G concept, although some studies explore a variety of managed charging options as well, or remain agnostic about the distinction.

VGI systems also can vary by the mechanism of user engagement—that is, how are PEV owners and operators being incentivized to participate in such a system? Perhaps most obviously, time-of-use (TOU) electricity pricing is available in some regions, where the price of electricity at any given time is tied to its availability, and changing prices are meant to control load across all electricity consumers. TOU rates alone can be a form of managed charging, providing incentive for PEV users to charge their vehicles at times that are lower cost (or more environmentally beneficial), whether manually, by a simple timer system, or with automatic controls. A similarly simple approach, TOU rates plus TOU net metering, would provide incentive for a user to enroll in a V2G system, allowing storage of electricity when rates are low and selling back to the grid when rates are high. A second financial incentive mechanism is revenue sharing, where an electric utility or third party aggregator strategically picks the most valuable markets to provide VGI to, then shares the enhanced revenues or savings with the user (see **http://nuvve.com**). For example, a PEV user or fleet operator may be offered a reduced electricity rate or a reduction in their monthly electricity bill in exchange for participation in managed charging or V2G. In one case, PEVs in a trial program operated by University of Delaware and NRG earned as much as $150/month (at the upper end of the range), of which half was provided to participating drivers (32). A third mechanism of engagement is education and environmental value—the idea that informing PEV operators that their participation in a VGI program can provide environmental benefits or enable more wind and solar energy generation might prompt some to enroll. Exploratory research suggests that approximately half of potential PEV buyers would consider enrolling in a VGI program if the only benefits offered were environmental (33).

Kempton and colleagues (7, 8, 13, 34, 35) have developed a framework for exploring V2G and identifying electric markets that have the greatest value, then developing systems to participate in those markets. The authors determined that vehicles must possess three elements to operate in V2G configuration: a power connection to the electricity grid, a control and/or communication device that remotely controls charging (typically via an aggregator combining PEVs) in order to provide grid services of value, and precision metering to enable participation in fast-response markets, and provide auditability (16, 36). Other phrases used to describe V2G concepts include V2X (37) (to signify any of vehicle-to-home, vehicle-to-building, vehicle-to-community and vehicle-to-utility configurations) as well as mobile energy storage systems (38), battery-to-grid (26), gridable vehicles (40), virtual power plants (41), and S3Ps (small portable power plants)

(42). In addition to the high-value regional markets mentioned above, a vehicle capable of V2G can, according to Habib et al. (43), offer eight different types of grid services, including active power regulation, supporting reactive power, load balancing by valley filling, harmonics filtering, peak-load shaving, reduction in utility operating cost and overall cost of service, improved load factors, and the tracking of variable renewable energy resources.

3. THE SOCIOTECHNICAL PERSPECTIVE AS AN INTEGRATIVE FRAMEWORK

To help understand the promise and challenges of VGI, this article views the related transport and electricity infrastructure as a sociotechnical system—looking at more than just the technical aspects of VGI that we define in the previous section. In his work on the history of the electric utility system, Hughes (44) argues that the generation, transmission, and distribution of electricity occur within a technological system that extends beyond the engineering realm. Such a system is understood to include a "seamless web" of considerations that can be categorized as technical, economic or financial, political, environmental, and social, making it sociotechnical. Large modern systems integrate these elements into one piece, with system-builders striving to "construct or... force unity from diversity, centralization in the face of pluralism, and coherence from chaos" (45, p. 52). If the managers succeed, the system expands and thrives while, simultaneously, closing itself. In other words, the influence of the outside environment on a sociotechnical system may gradually recede as the system expands its reach to encompass factors that might otherwise alter it. Thus, the concept of a sociotechnical system helps reveal that technologies must be understood in their societal context, and that the different values expressed by inventors, managers, and consumers shape technological change. System builders, it follows, must overcome a complex milieu of sociotechnical obstacles to reap benefits. A salient insight from the sociotechnical approach is its focus on the interrelationship of linkages between elements and coevolutionary processes, with **Figure 1** offering an illustration of the sociotechnical system surrounding modern car-based land transportation (46).

We apply a sociotechnical approach to the VGI concept more specifically by breaking down our analysis into four distinct categories, which are summarized in **Table 2**. First, we discuss

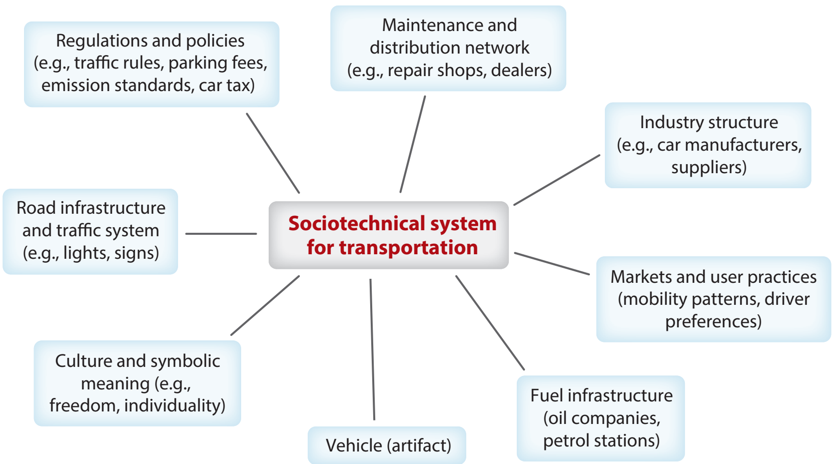

Figure 1

A sociotechnical system for personal automotive transportation. Adapted from Reference 46 with permission.

Table 2 Overview of sociotechnical dimensions to a vehicle-grid integration (VGI) transition

Dimension	Inclusive of	Example(s)
Technical	Technology, infrastructure, and hardware	Vehicle performance, grid interconnection, communication, battery degradation
Financial	Price signals, economics, regulatory tariffs	Capital cost of VGI charging stations, vehicles, batteries and interconnectors, revenues, cost savings
Socio-environmental	Broad social costs and benefits	Mitigated greenhouse gas emissions, air pollution, integration with renewable sources of energy, externalities
Behavioral	Consumer and user perceptions, attitudes, and behavior	Consumer perceptions of all of the above, including benefits, inconvenience, distrust, confusion, and range anxiety

technical or technological elements such as batteries and charging infrastructure, tires on vehicles, and interconnections to the electricity grid. Next, we explore financial and economic elements encompassing the cost of that technology as well as availability of fuel and any affiliated cost savings and revenues generated. A third category is socio-environmental, and how it relates to overall benefits (or costs) to society. A fourth category focuses on the individual behavior of consumers and users, namely the owners and operators of PEVs that might take part in VGI programs.

In laying out the following sections, it is not our intent to suppose that demarcations between technical, financial, socio-environmental, and behavioral dimensions are really distinct, separate classes. The entire point of systems approaches is that such impediments are seamlessly interconnected; dividing the social from the technical, or even the economic from the environmental, is counterproductive and dangerous, given it misses the point that such factors exist in an interstitial and interdependent network. In other words, it is a heterogeneous combination of sociotechnical factors that determine whether VGI technologies will achieve widespread acceptance or face consumer rejection. Since Sovacool & Hirsh's (6) 2009 sociotechnical analysis of PEVs and V2G systems, no other VGI studies have taken an explicit sociotechnical approach. Here we draw from different studies that tend to focus on one or two aspects of this framework and in effect compile a state-of-the-art view of VGI research—identifying gaps in Section 6.

4. THE FUTURE PROMISE OF VGI

As the sociotechnical heuristic suggests, the benefits of VGI systems do indeed cut across technical, financial, socio-environmental, and consumer dimensions, each of which is elaborated here.

4.1. Technical: Improved Grid Efficiency

The reasoning for VGI starts with an analysis of the duty cycle of most light-duty vehicles. A typical vehicle is on the road only 4–5% of the day; as such, 95% of the time, personal vehicles sit unused in parking lots or garages, typically near a building with electrical power (47). The first technical benefit is that VGI automobiles can turn unused equipment into useful services to the grid.

The second benefit derives from the underutilization of many utility resources, an implication of the necessity that electric generation and transmission be sufficient to meet the highest expected demand for power at any time. Except for these periods of peak use, the power system could generate and deliver a substantial amount of electrical energy, for example, to fuel a nation's vehicles at a much lower cost than typical gasoline or diesel prices. In the United States, for instance, 8 to 12% of peak electricity demand occurs within just 80 to 100 hours during the year (48). Because much of the generating capacity remains unused, one study estimated that as of 2007, 84% of all light-duty vehicles, if they were suddenly converted into PEVs in the United States, could be supported by the existing electric infrastructure, providing they drew power from the grid at off-peak times. Consequently, utility companies would earn extra revenues during these off-peak periods (49).

Denholm & Short (50) also modeled the addition of PHEVs to recorded utility loads and considered their impact for peaking generation and reserve capacity. Assuming a PHEV penetration of 50% of total light-duty vehicle stock, the study found that utilities could utilize large amounts of existing capacity to power PHEVs as long as they retained some control over when charging occurs. Put differently, a company could increase revenues if they could restrict charging of the vehicles to off-peak times. The National Research Council concurred in a 2010 report, noting that "No major problems are likely to be encountered for several decades in supplying the power to charge PHEVs, as long as most vehicles are charged at night" (51, p. ix). More recently, Saxena et al. (52) argued that since PEVs operate at higher efficiency than conventional ones, and seldom exceed 100 km of daily travel, 85% to 89% of passenger vehicle drivers across the United States could be satisfied with electric vehicles charging only within standard outlets at their homes. That study also found that under extreme conditions where trips involve steep hills, 70% of passenger vehicle drivers across the United States would be satisfied with PEVs. Needell et al. (53) estimated that 87% of vehicle-days in the United States could be met using a currently available BEV charged just once per day. To be fair, this study makes the common misjudgment that vehicle purchase decisions will be made based on adequacy for much but not all daily driving; other studies assume a larger battery is required for most consumers, to meet most trips in a year (54, 55). A similar study from Germany reached the same conclusion, noting that electrifying the fleet of German passenger cars would only increase total electricity consumption by 2% nationally (56).

Taking a slightly different perspective, Kempton & Tomić (13) compare the relative power of the US electric generation with the US light-duty vehicle fleet in 2005. In **Table 3** we provide an updated version of that analysis. Surprisingly, the total prime mover power of the 2015 light-duty vehicle fleet is 40 times that of all electric generators across the country (compare first with middle column in **Table 3**) (13). In short, BEVs and PHEVs are not necessarily cost-effective for producing an abundance of kWh of energy, but they could be cost-effective in providing kW of power capacity that will not be used continuously. Put another way, it could be more cost-effective to use PEVs for grid services otherwise provided by backup and peaking power plants, especially given that the response of PEVs can be as rapid as tens of milliseconds.

4.2. Financial: Electric Utility Revenues

VGI systems can bring financial and economic benefits. Automobiles in a VGI configuration could provide additional revenue to owners that wish to sell power (discussed in detail in Section 4.4, the section on behavior and consumers) or grid services back to electric utilities. Although the specifics would differ according to local electricity markets, VGI vehicles could become more like "cash cows" (products that generate steady profits) that produce income from existing equipment and less like vehicles that merely consume energy (6). The earliest analyses of VGI estimated a high value for V2G based on the marginal price for peak-load services and regulation services (i.e., second-to-second load balancing), indicating that the net-present value of a PEV providing peak-power could be up to $2,400/year (7), whereas a PEV providing regulation could earn up to US dollars ($)5,000/year. More recent analyses estimate lower values of VGI, typically by using economic models that represent system dynamics in price and quantity. The results of these VGI economic modeling studies vary widely, showing that VGI could produce monetary benefits in the range of $100–$300/year per participating vehicle in the study year (60). As an illustration,

Table 3 Utility electric generation compared with the light-duty vehicle fleet (2015; for the United States)[a]

Metric of comparison	Electric generation system	Current light-duty vehicle fleet (mechanical power)	Projected light-duty vehicle fleet, if BEVs 50% of light-duty vehicle stock (electrical power)
Number of units (vehicles and power plants)	7,453[b]	240,155,000[i]	120,180,000
Average unit power (kW)	142,769	171 kW_m[j]	10 kW[n]
Total system power capacity (GW)	1,064[c]	40,994 GW_m	1,202
In-use duty cycle	42%[d]	4%[k]	4%
Response time (off to full power)	Minutes to hours[e]	Seconds	Tens of milliseconds to seconds
Design lifetime (h)	80,000–200,000[f]	4,200[l]	4,200+
Capital cost ($US/kW)	1000–7,000[g] $/kW	$90[m] $/$kW_m$	50–150[o] $/kW
Cost of electric energy ($US/kWh)	0.10[h]	n/a	0.19[p]

Abbreviations: BEV, battery electric vehicle; kW, kilowatt of electrical power; kW_m, kilowatt of mechanical power.
[a]The table is based on Kempton & Tomić's (13; see table 1) data regarding implementation, with the original 2004 data updated here to reflect 2015 data.
[b]Data are per the US Energy Information Administration's (EIA's) Electricity Data Browser (**https://www.eia.gov/electricity/data/browser/**).
[c]Data are per the EIA's table 4.7.A., Net Summer Capacity of Utility Scale Units by Technology and by State, 2015 and 2014 (Megawatts) (**https://www.eia.gov/electricity/annual/html/epa_04_07_a.html**).
[d]EIA; total generation (table 7.2.B from EIA 2017—Electricity Net Generation—divided by total system power capacity * 8,760 h/year.
[e]Gas turbines about 10–15 min; large coal and nuclear several hours to 1 day.
[f]A gas turbine peaking plant might have a 20-year design lifetime, intended to be run 4,000 h/year, thus a design life of 80,000 h. A large coal plant with a design lifetime of 30 years, operated at a 75% capacity factor or approximately 8,000 h/year, would have a lifetime of approximately 200,000 h (see 13, table 1).
[g]Data show new generation, overnight cost: gas CC $978, wind $2,438, coal (PC) $2,844, nuclear $6,835; see Reference 57.
[h]Data are per the EIA's Electricity Data Browser (**https://www.eia.gov/electricity/data/browser/**), showing annual, average US retail price for 2015. Peak power prices can be several times higher over some hours.
[i]See Reference 58, table 1–11, Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances, "light Vehicles," short plus long wheel base, 2015.
[j]Data are per Reference 59; 229 hp = 170.7 $kW_{electrical}$.
[k]Data are per Reference 13.
[l]12-year life x* 8,760 h/year * 4% duty-cycle = 4,200 h.
[m]Data show the cost per kW_m of drivetrain, not for the whole vehicle (per Reference 13—inflated by 1.5).
[n]Typical US apartments usually can provide 7 to 10 kW; US single-family detached houses typically provide 22 kW. Here we use 10 kW as a conservative average.
[o]Data show the incremental capital costs to add V2G to an EDV, not total cost. If bidirectional charger and communications hardware adds $US 500–1,500 to a 10-kW charger, that would be $50–$150 per kW of charge rate.
[p]Cost is estimated as retail electricity (14 c/kWh) + two-way losses (20%) + battery degradation (2 c/kWh) = 19 C/kWh; lower if most charging is done off-peak or efficiency is improved.

Table 4 summarizes seven VGI studies according to various assumptions about consumers, PEV uptake, VGI system (e.g., V1G or V2G), time frame and location—all of which can greatly impact estimates of financial benefits (M.Wolinetz, J. Axsen, J. Peters & C. Crawford, manuscript under review). In particular, modeling studies tend to estimate higher values when they account for more potential VGI benefits, such as avoiding capacity additions (61, 62). In Section 6.3 we provide more discussion of how future research can improve upon these modeling approaches and assumptions, yielding more realistic and useful estimates of VGI value.

In exploring the potential revenue benefits of V2G at the utility level, the Pacific Northwest National Laboratory (PNNL) in the United States assessed the revenue and cost streams of two sample utilities, Cincinnati Gas & Electric (CGE) and San Diego Gas & Electric (SDG&E) (66). They concluded that with 60% penetration in the light-duty vehicle market, PHEVs would

Table 4 Illustrative summary and comparison of VGI modeling approaches and estimates of net-present value[a]

	Lund & Kempton (2008)	Sioshansi & Denholm (2009)	Lyon et al. (2012)	Druitt & Früh (2012)	Dallinger et al. (2013)	Weis et al. (2014)	Wolinetz et al., under review
PEV adoption	*Exogenous*: 100% PEV market share	*Exogenous*: 0% to 15% PEV market share by scenario	*Exogenous*: 0% to 60% PEV market share by scenario	*Exogenous*: 0% to 30% PEV market share by scenario	*Exogenous*: 25% PEV market share	*Exogenous*: 1% to 15% PEV market share by scenario	*Endogenous*: PEV adoption simulated
PEV usage (driving and recharging)	*Exogenous*: Hourly statistics with percent parked/driving	*Exogenous*: Hourly statistics with percent parked/driving	*Exogenous*: Hourly statistics with percent parked/driving	*Exogenous*: Stochastic inputs based on survey data	*Exogenous*: Stochastic inputs based on survey data	*Exogenous*: Hourly statistics with percent parked/driving	*Exogenous*: Driving diary data for individual vehicles
PEV participation with VGI	*Exogenous*: PEVs charge at night, or utility minimizes costs with V1G charging or V2G.	*Exogenous*: Utility uses V2G to minimize system costs.	*Exogenous*: PEVs charge at night, or utility minimizes costs with V1G.	*Exogenous*: PEV owners minimize charging cost in response to real-time pricing.	*Exogenous*: PEV owners minimize charging cost in response to real-time pricing.	*Exogenous*: PEV owners minimize charging cost in response to real-time pricing.	*Endogenous*: V1G participation is simulated.
Electricity capacity	*Exogenous*: Fixed capacity, wind capacity ranges from 0% to 100% by scenario.	*Exogenous*: Based on capacity in Texas in 2005 (10% wind)	*Optimized* capacity additions	*Optimized* capacity additions with scenarios exploring impact of greater wind capacity	*Exogenous*: Fixed capacity, wind and solar capacity produces 50% of electricity	*Optimized* capacity additions with scenarios exploring impact of greater wind capacity	*Optimized*
Hourly generation (i.e., utilization)	*Optimized*	*Optimized*	*Optimized*	*Optimized*	*Optimized*	*Optimized*	*Optimized*

(*Continued*)

Table 4 (*Continued*)

	Lund & Kempton (2008)	Sioshansi & Denholm (2009)	Lyon et al. (2012)	Druitt & Früh (2012)	Dallinger et al. (2013)	Weis et al. (2014)	Wolinetz et al., under review
Time dimension and resolution	Hourly in 2020	Hourly in 2005	Hourly with time steps to 2030	15 minutes with time steps to 2020	Hourly in 2030	Hourly with time steps to 2025	Hourly with time steps to 2050
Region and scale	National grid, Denmark	Regional grid, Texas	Regional grids, eastern United States	National grid, United Kingdom	Regional and national grid, California and Germany (respectively)	Regional grid, New York	Connected regional grids, Alberta and British Columbia, Canada
VGI impact	Impact reduces excess wind generation by roughly one-third.	V2G avoids 20–30% of the GHG emissions resulting from PEV electricity demand.	Savings with VGI have net-present value of $50–$450 per vehicle per year, and are higher where new capacity must be added.	Savings of VGI are $75-$225 per vehicle per year, and are higher with more wind capacity.	Impact reduces excess wind and solar generation by roughly two-thirds.	Savings of VGI are $70–$120 per vehicle per year, and are higher with more wind capacity.	Savings of VGI are $50–$125 per vehicle per year, and are higher with more wind and solar capacity.

Abbreviations: GHG, greenhouse gas; PEV, plug-in electric vehicle; VGI, vehicle-grid integration; V2G, vehicle-to-grid.

[a]Table adapted from M. Wolinetz, J. Axsen, J. Peters & C. Crawford (manuscript under review). Some studies suggest that some types of vehicle fleets could earn even more revenue than passenger vehicles, especially fleets with predictable driving patterns (63). For example, Noel & McCormack (64) found that compared to diesel-fueled school buses, in certain conditions VGI-enabled electric school buses could save school districts approximately $6,000 per seat in net-present value, or roughly $430 per seat per year over the projected 14-year average lifespan of a diesel school bus in Delaware. Similarly, De Losi Rios et al. (65) found, compared to diesel-fueled trucks, V2G-enabled electric trucks could have 5–11% lower lifetime ownership cost.

generate income during off-peak hours and help the companies recover their fixed costs and borrowing expenses more quickly than if they did not sell power to vehicles. By doing so, the utilities could reduce overall rates by as much as 0.4 cents per kWh for CGE and 5.0 cents per kWh for SDG&E. In other words, sales of power to PEVs could improve the companies' load factors (i.e., allow the companies to use their equipment more effectively) and reduce the overall cost of service on a per-kilowatt-hour basis.

Emerging research is also exploring the potential for VGI business models among different types of agents, intermediaries, or aggregators—that is, VGI deployment strategies that likely bring profit to a particular organization, providing incentive for that organization to manage the VGI potential of some subset of vehicles (67–69). For example, studies have found that parking garages might have particularly strong potential for a VGI business model, where a large set of PEVs could be efficiently charged during the daytime, using a V1G or V2G setup (70).

4.3. Socio-Environmental: Mitigated Emissions and Integration of Renewables

The socio-environmental promise of VGI is more difficult to classify, but nonetheless still salient. Benefits here include reduced air pollution and climate change, and increased integration and penetration of renewable sources of energy.

VGI-enabled automobiles could reduce GHG emissions from the transport sector substantially, although the majority of emissions savings have nothing to do with vehicles being VGI capable, only with their being electric. Much of this benefit comes from the nature of PEVs. Using an extensive database on carbon dioxide (CO_2) emissions from automobiles in the United States, researchers from the American Solar Energy Society calculated that for each mile driven in a PHEV instead of a gasoline-powered vehicle, CO_2 emissions would be reduced an average of 42% (71). In the United Kingdom, PEVs have the potential to reduce CO_2 emissions by 62–65% compared to internal combustion vehicles by 2030 (72). Further studies reiterate the same general conclusion: PHEVs and BEVs can reduce GHGs significantly, even when operating in a wide variety of conditions (73–79).

Concomitant with carbon reductions are reductions in other types of air pollution. For instance, PNNL projected that pollution from total volatile organic compounds and carbon monoxide emissions would decrease by 93% and 98%, respectively, under a scenario of VGI penetration, and total nitrogen oxides (NO_x) emissions would also be reduced by 31% (49). In tempering their findings, the authors cautioned that total particulate matter emissions would increase by 18% and SO_x emissions would increase by 125% if the PEVs were powered by electricity from coal-fired plants; however, the pollution would be transplanted from local urban areas to the more distant locations of power plants. The authors also pointed out that this suboptimal scenario could be avoided and net gains could be made if electricity came from natural gas or renewable sources of energy. Another study found that by changing generator dispatch, a PHEV fleet in V2G configuration accounting for 15% of light-duty vehicle usage will actually decrease net NO_x emissions even during the ozone season, despite the additional load for charging, and that by adding services such as spinning reserves and storage, sulfur dioxide (SO_2) and NO_x emissions would be reduced even further (80).

Finally, a VGI system can further accrue environmental benefits by providing storage support for intermittent renewable-energy generators (41). In other words, the batteries in the vehicles could store electricity produced by wind turbines, and provide the power back to the grid when needed (81, 82). The power produced from the turbines fluctuates greatly due to wind gusts, cloud cover, thermal cycles, the movement of weather fronts, and seasonal changes (83, 84). Given that they produce most of their electricity at night, just when PEVs would need to be recharged, a VGI strategy could greatly help level daily fluctuations in wind power (85, 86). PEVs could offset the need for spinning reserves and load management necessary to integrate these intermittent resources [and others, such as solar photovoltaics (87)] into the grid (88). Also, VGI-engaged PEVs could replace (or more likely, supplement) large-scale pumped hydroelectric and compressed air energy storage systems, which have already proven effective for enhancing the value of renewable-energy technologies (89). As examples, VGI grid modeling studies already demonstrate that V2G or controlled charging schemes can help increase the use of intermittent wind and solar and cut GHG emissions in the Texan (80), Californian, and German electricity grids (15), and in Denmark's (14).

4.4. Behavioral: Cost Savings and Environmental Benefits

The two main benefits that VGI can offer consumers clearly flow from two of the more general benefits we discuss above: cost savings and environmental benefits. Discrete-choice modeling research in the United States finds that potential BEV drivers would require a high degree of annual compensation to enroll in some form of V2G program, ranging from 2,000 to more than $8,000 per year (90). A Canada-based discrete choice survey looked more broadly at potential PEV (including PHEVs) buyers' interest in a VGI program that controlled the timing of charging (91). That analysis identified four different consumer segments, including a "cost-focused" segment representing 33% of the sample of more than 1,700 new vehicle-buying households. Notably, the policy scenarios that offered a 20% savings on electrical bills for enrollment in a VGI program (with no environmental benefit) resulted in the highest simulated rates of respondent participation, in the realm of 63–78%. The authors also applied their survey instrument to a sample of Canadian PEV owners (or PEV "Pioneers"), who on average require two to three times more financial compensation (as a monthly payment) to enroll in a VGI program than potential future Mainstream buyers (20). One explanation for this difference could be that PEV Pioneers have direct experience with PEVs and have a better sense of how they would value engagement in a VGI program.

The second potential benefit to consumers is reduced environmental externalities, provided that the VGI program in question is used to reduce the environmental impacts of electricity generation—particularly by facilitating the use of intermittent sources of renewable energy. Axsen & Kurani (92) explored the idea of pairing the sale of a PEV with consumer enrollment in a renewable electricity program, using a web-based survey of 1,502 US new vehicle buyers (1,064 conventional vehicle owners, 364 HEV owners, and 74 PEV owners). Offering a green electricity program to accompany a PEV purchase increased stated interest in PEVs by 23% among the conventional (Mainstream) vehicle owners. Similarly, the Canada-based stated preference survey noted above identified two consumer segments (representing 46% of the sample) that stated a positive, statistically significant willingness-to-pay for a VGI program that would support the use of intermittent, renewable forms of electricity (93). In particular, the "renewable-focused" segment (19% of the sample) would be willing to pay (or lose) an extra $98 (CDN) per year for a 10% increase in their PEV's usage of renewable electricity. However, the resulting choice simulation model indicated that a VGI program offering to power PEVs with 100% renewable energy (compared to a program with status quo electricity) would increase overall enrollment among potential PEV owners from ~53% to 59%—where a 20% savings in electricity bill was more highly valued. A comparable sample of PEV Pioneers was found to value inclusion of renewable electricity seven times more highly than the Mainstream sample (20). In short, environmental benefits might be one important motivator for Mainstream PEV buyers, but on their own such benefits are not likely enough to motivate substantial PEV buyer enrollment in VGI programs.

5. THE CHALLENGES AND BARRIERS TO VGI

A sociotechnical lens not only provides a useful frame for which to examine hopeful benefits; it also implies the existence of a seamless web of technical, financial, socio-environmental, and behavioral challenges.

5.1. Technical: Communication and Battery Degradation

The benefits of VGI services do come with some significant technical barriers including communication and control and battery integrity and charging.

Firstly, enabling PEVs of various shapes and sizes to provide VGI services depends on additional electronic, communication, and control costs (94). Hein et al. (26) note that V2G commercialization could depend on technical enhancements in dispatch, modeling, and charging communication. A slew of other engineering studies confirm that meaningful technical obstacles involve new patents and design features for large-scale communication, control, and coordination systems (96–102), although early work at the University of Delaware suggests they are surmountable (32). The impact of PEV charging on medium voltage distribution grids also remains unclear—with the very real risk that various bottlenecks could occur and that charging could degrade parts of the grid, especially low voltage transformers and line capacity violations (85). Green et al. (103) add that the penetration of PHEVs will have a "drastic impact" on many distribution grids.

Secondly, providing VGI services will invariably reduce battery life; the question is, how much in relation to battery use for driving only (104). The only published quantitative answer comes from Honda: Testing the challenging case of a continuously running grid service over the warrantee life of a vehicle, they find that driving caused 8% battery degradation and continuous VGI added another 2% (105). Although fast chargers (generally, over 20 kW) offer users the convenience during trips, the high-power demand often will exceed rated grid power capacity, thus requiring costly upgrades, and/or the user may see a cost in demand charges or capacity payments (106). Although Peterson et al. (107) found only a mild effect between V2G services and battery wear, Bishop et al. (108) concluded that V2G provision will require multiple, additional battery replacements over the lifetime of the vehicle (108). Marongiu et al. (109) simulated 100 BEV models with two different lithium-ion battery pack configurations through accelerated aging tests, and found that battery performance will differ substantially based on battery chemistry, weather and temperature, and driving practices—exceeding expectations in some situations, but failing to meet them in others. Juul (110) found that marginal benefits decrease for V2G automobiles the larger the battery, and that in larger vehicles such as vans, diesel vehicles are more preferable (from a cost perspective) than for car BEVs. Neubauer et al. (111) assessed the interplay of three PEV types and ranges, three maximum states of charge, and almost 400 driving patterns (simulating more than 21,400 unique cases) and noted that, ironically, one needs larger batteries with maximum state of charge to accommodate most drivers but low driving ranges, a clear paradox. Saxena et al. (112) add that the common definition for battery end-of-life at 70 to 80% of capacity results in early retirement for scores of batteries that could still meet the daily travel needs of most drivers.

5.2. Financial: First-Cost Hurdles

The financial promise of VGI systems is not absolute either and remains constrained by the first-cost hurdle. VGI-enabled PEVs can be more expensive than regular PEVs, which are already more expensively priced than their conventional alternates. As noted in the behavioral section below, some consumers do not care enough about cost savings to substantially value VGI revenue/sharing—essentially undervaluing fuel or electricity costs savings compared to what a rational actor model would predict. Indeed, one survey among California households found that not one of them had estimated present value of fuel savings as part of a decision to purchase a new vehicle (113). Another study of drivers in California concluded that no single respondent analyzed vehicle fuel costs in a systematic way, almost none tracked gasoline costs over time, and few considered transportation fuel costs in household budgets (114). The study found that drivers rapidly forgot the price they paid for gasoline on a particular day, and that drivers "lack the basic building blocks of knowledge" (114) needed to make intelligent decisions about fuel economy.

For those consumers that do consider fuel economy when purchasing a vehicle, the International Energy Agency (IEA) found that buyers expect vehicle efficiency improvements to pay for themselves in the first three years or less (115). In line with the tendency for consumers to greatly discount future cost savings, Parsons et al. (90) found that respondents in the United States used a 53% discount rate in valuing revenue from V2G contracts.

5.3. Socio-Environmental: Negative Externalities

Another class of challenges falls into the socio-environmental category and encompasses the negative externalities associated with VGI systems, especially those related to the increased adoption of PEVs. Although both PEVs and a VGI configuration have the potential to yield environmental benefits, they do not come without negative impact. For example, a transition from internal combustion engines to electric power is likely to increase the consumption of electricity. This could produce negative impacts on water availability, especially because fossil fuel and nuclear power plants—which dominate the electricity generation sector—require large amounts of water for the production of steam and for cooling processes (116). The added water intensity associated with PEVs makes it difficult to electrify transport in regions where water is scarce—a prevalent condition in many large urban areas and arid regions across the globe (117). Furthermore, the BEV manufacturing process can be polluting, and it also involves the mining of rare earth minerals and other elements (for batteries, drivetrains, and components) that do have environmental costs (118, 119).

Although negative externalities can be a legitimate concern, the positive externalities from VGI appear to outweigh the negative ones. For instance, two recent analyses tested nearly 86 million different combinations of wind turbines, solar panels, natural gas power plants, VGI cars, and electric heat devices, modeling system reliability in the northeastern part of the United States for four years of operation (120, 121). Compared to a baseline of business as usual, the simulation calculated that V2G is responsible for a reduction of $158.6 billion in externalities in net-present value over 25 years. This amount translates to $6.3 billion a year, roughly, or equivalent to $174/car/year of net social and environmental gain.

5.4. Behavioral: Inconvenience, Distrust, Confusion, and Range Anxiety

Consumer-based research has identified several potential barriers to the uptake of VGI programs. First is the potential inconvenience of a program, particularly in how the program affects the available range of the PEV at any given time, including V2G programs that might "sell off" the electricity in the vehicle as well as V1G programs that might delay or slow the speed of charging. Such alterations in charging could interfere with consumers' driving behavior or lifestyle, present a threat in the case of emergency, or increase the proportion of gasoline-powered miles relative to electricity-powered miles in the case of PHEVs. A US-based stated choice experiment found that new vehicle buyers are fairly risk-averse regarding BEV range (the study did not include PHEVs), preferring a high guaranteed minimum range across various V2G scenarios (90). For example, reducing the guaranteed minimum range from 175 miles to 125 miles was valued as equivalent to a loss of $500 in upfront value, and reducing the charge to 75 miles is equivalent to a loss of $4000. A Canada-based stated choice experiment identified that when comparing VGI scenarios, survey respondents on average were willing to pay an extra $250 (CDN) to increase the morning charge of their 64-km-range PHEV by 10 km, with one charge-focused segment (representing 33% of the total sample) that was willing to pay more than $300 per year (122). On average, the discrete choice simulation model indicated that consumer enrollment in a VGI program would decrease by 7 to 12 percentage points with a 20% decrease in guaranteed PEV driving range. In semistructured interviews with 21 of these households (a purposive subsample including a broad range of demographic groups), 10 indicated discomfort with VGI, expressing that they prefer to keep 100% charge in their PEVs for "peace of mind" (123).

Indeed, concern with how VGI engagement may impact the electric-powered range of a PEV has provoked some to even coin the term range anxiety to express worries over how far BEVs can go in between charges (124, 125). One survey of drivers in the United States found that battery range represented the single most important concern expressed about BEVs, even more than cost (126). Across the European Union, 74% of consumers expected a range of 480 km before having to recharge, yet the usual distance driven by that group is 80 km per day (127). However, early critics of this so-called range anxiety framing discovered that when suitably motivated, many California households were able to find ways to organize their multi-car households to accommodate a limited-range vehicle (128). Furthermore, this concept of range anxiety does not apply to PHEVs, due to their ability to also be powered by a gasoline (or other liquid fuel) engine.

A second, related concern is the potential for consumer distrust in their electricity utility or the third party that is running the VGI program. The Canada-based survey noted above found that 24% of the new vehicle buying respondents believed that a VGI program would be an "invasion of privacy," and 39% indicated that a VGI program might "take control away from me in a way that I would not like" (129). Several of these households explained their concerns with trust in follow-up structured interviews; for example, one consumer worried: "what happens when the computer glitches, and I go downstairs and I go, 'oh my car's not charged'?" (130, pp. 170–71). Such research has informed some demonstration V2G programs. One program run by Nuuve provides simple defaults but always gives the driver the ability to schedule typical trips, plan for one specific long trip, or simply request filling the battery right away, all from either a web browser or a mobile app such as those offered by Apple for iPhones.

A third concern is the potential for consumer confusion regarding the concept of PEVs, where Mainstream new vehicle buyers tend to be confused about the basic concepts of PEV types, such as how hybrids differ from PHEVs and BEVs (20). Interviews with Canadian new vehicle buyers found that most Mainstream participants had a difficult time understanding the concept of VGI, including the notion that timing of PEV charging could improve grid efficiency or reduce environmental impact (130). In contrast, PEV owners or "Pioneers" have a much easier time grasping the concept of VGI (123).

A fourth potential barrier to VGI deployment is consumer concern over battery degradation. Exploratory research suggests that this concern is only currently present among PEV Pioneers, as the vast majority of Mainstream new vehicle buyers do not have enough technical understanding to be worried about battery degradation. In semistructured interviews with 22 Canadian PEV owners, only a few households brought up battery degradation without being prompted (123). As stated by one participant, "the only condition I would really need would be . . . a guarantee that it's not damaging to the vehicle in any way or degrading the battery" (123, p. 173). Accordingly, some

Original equipment manufacturer (OEM): such as an automobile manufacturer

households stated they would need either a guarantee from an electric power utility, monetary compensation, or an extended battery warranty to accept VGI. Original equipment manufacturers (OEMs) are apparently aware of this potential issue, given those few now offering VGI vehicles that explicitly cover V2G with the warrantee (for example, Nissan Europe honors the full warrantee on Leaf and e-NV200 electric vehicles as long as power does not exceed 10 kW) (131).

Concerns about battery degradation can become more elevated in some cases of fleets and commercial usage. Although the data are dated, taxis offer one example, as they tend to have far heavier duty cycles than privately owned passenger vehicles. In 2008, researchers in New York surveyed the managers of 68 taxi fleet companies, employing more than 13,000 taxi drivers in New York City, about their preferences for PHEVs (132). The study group found that the managers believed the average lifetime for their fleet vehicles was a mere 3.7 years and that concerns about battery replacement expenses for PHEVs were "pervasive." As a result, the authors concluded that without government intervention, PHEV penetration in the New York City market would remain limited.

Although not directly specific to VGI, we note that a final potential market barrier to the PEV market relates to the supply of the vehicles. Matthews et al. (133) surveyed consumer experiences with several different "PEV-certified" car dealerships in Canada, finding that many dealerships were unenthusiastic about selling PEVs, often did not carry a PEV in stock to show the consumer, and in some cases provided misinformation about PEVs. In related research, Cahill et al. (134) found that many California dealers and salespersons expressed antagonism toward PEVs, given they result in "little or no up-front profit on sales" as well as fewer warranty repair and service maintenance opportunities. Consequently, the study noted that "PEV buyers universally report lower satisfaction with the dealer purchase experience" (134, p. 21). Franchise laws, protectionism, and prohibitions on direct sales act as a further constraint, with Tesla in particular forbidden under some state laws to sell vehicles in the United States (135).

6. RESEARCH GAPS AND A CRITICAL RESEARCH AGENDA

The sociotechnical perspective not only offers a comprehensive lens by which to appreciate the promise of and challenges to a VGI transition, it also reveals at least four critical research gaps, including the need to broaden VGI cases, explore how to overcome transformative failures, study and more realistically model VGI users, and embrace interdisciplinary and multi-method approaches.

6.1. Broadening the Set of VGI "Cases"

Future VGI research could improve by exploring a broader variety of "cases," that is, arrangements of vehicles, users, and system characteristics that could transition to a VGI system. As noted in Section 3, VGI literature tends to focus on the case of privately owned, light-duty passenger vehicles, models of BEVs rather than PHEVs, and V2G rather than V1G. There is a need for more comprehensive, comparative work that could explore and model the different benefits and drawbacks that would face different vehicle types (light-duty versus medium- and heavy-duty vehicles), owner groups (passenger vehicle owners versus fleet operators), ownership arrangements (private versus car sharing), technology types (PHEV versus BEV, as well as degree of automation), degrees of VGI (different types of V1G and V2G), and methods of VGI engagement (TOU pricing, revenue sharing, controlled charging programs, or voluntary enrollment). Such comparative work could help researchers, policymakers, and other stakeholders to better prioritize efforts for VGI development toward opportunities that are more feasible in different time frames and more likely to yield societal or financial benefits.

6.2. Overcoming Transformative Failures

Another substantial gap in the literature is how a large-scale transition to VGI can be achieved, overcoming the long-history of hypes, disappointments, and failed transitions to alternative fuels and low-carbon technologies (136).

Future research could draw from Weber & Rohracher's (137) framework of 12 different failures that prevent transformative change, divided into three different categories that we amend with VGI examples in **Table 5**. First are market failures, which include knowledge spillover effects and investor short-sightedness that together lead to underinvestment in VGI innovations, which by nature are likely to take a long time to mature and produce revenue (due to the delayed turnover of vehicle stock and electricity infrastructure). Second are structural system failures, which include a lack of the infrastructure and institutions needed to support a large-scale transition to VGI. Research could focus on better understanding and assessing the effectiveness of efforts to overcome such barriers. For example, research could draw from the California's Independent System Operator's efforts to consult with a wide variety of stakeholders from private and public organizations to identify a VGI "roadmap," including definitions of VGI cases, research needs for assessing VGI benefits and barriers, and efforts to integrate policies and codes across institutions (5). Third are transformative system failures such as a lack of shared vision among key stakeholders

Table 5 Overview of vehicle-grid integration (VGI) failures in the context of transformative change[a]

	Type of failure	Examples of potential barriers to VGI
Market failures	Information asymmetries	Technology uncertainty among private investors leads to underinvestment in VGI-related technologies.
	Knowledge spill-over	Public-good aspect of VGI innovation leads to underinvestment in R&D.
	Externalization of costs	Failure to price negative environmental externalities could exacerbate their impacts.
	Over-exploitation of commons	Poorly designed VGI systems could overexploit public-good aspects of the grid.
Structural system failures	Infrastructural failure	Lack of necessary VGI infrastructure, including grid capacity, chargers, and meters, could stymie development.
	Institutional failure	Absence of needed laws, regulations, and standards could slow a VGI transition.
	Interaction or network failure	Small, closely-tied groups develop and pursue VGI visions that lack infusion of new ideas.
	Capabilities failure	Lack of competencies and resources regarding VGI at firm and actor levels impede innovation.
Transformational system failures	Directionality failure	Lack of shared vision regarding the goal and direction of VGI decelerates the VGI transformation process.
	Demand articulation failure	Lack of space to explore and understand user (consumer) needs disables the uptake of VGI.
	Policy coordination failure	Lack of multi-level policy coordination to support VGI, e.g., lacking provisions in low-carbon vehicle, fuel, and electricity policy, disincentivizes low-carbon VGI systems.
	Reflexivity failure	Inability of system to adapt to change regarding VGI technology and user and firm behavior leads to lack of learning.

[a]Table based on table and quotations from Reference 137 with data adapted to VGI examples by authors.

or "directionality failure," where electric utilities and automakers may have very different visions about VGI, and different ideas about the likelihood of a VGI future being successful. Referring again to VGI stakeholder consultations in California, one stakeholder was quoted as saying that "communication and control technologies and consistent technology platforms are essential for the VGI market to grow. Varying design standards for EVSE [recharging equipment] could lead to limited access for VGI services" (5).

A related gap and line of inquiry is explicit exploration of the policies needed to overcome these transformative barriers, including Weber & Rohracher's (137) notion of policy coordination failure. For example, with the goal of GHG emissions reduction, a strong carbon tax might provide incentive for the transportation and electricity sectors to innovate in a low-carbon direction, potentially including VGI development. However, the transformative barriers noted above (beyond just environmental externalities) indicate that a carbon tax alone might not be enough (138). Many regions instead rely on a patchwork of sector-specific climate policies, for example, California's low-carbon fuel standard (LCFS) and zero-emissions vehicle (ZEV) mandate for the transportation sector, and a renewable portfolio standard for the electricity sector. Although such policies can be complementary, they are rarely planned out in a deliberate way across sectors. California's LCFS regulates the lifecycle carbon intensity of fuels used for transportation, where VGI could potentially reduce the carbon intensity of electricity used for PEVs. It is not clear if the policy would provide credit for the potential GHG reductions that could result from VGI-based electricity in comparison to a "convenience charging" approach to PEVs—thus there is less incentive for stakeholders to innovate in the direction of low-carbon VGI. Future research can better explore the suite of policies that are needed to incentivize the innovations and efforts that would inevitably be part of a full transition to VGI. The sidebar Transformative Failures in Practice: The Case of Alternating Current Chargers describes another transformative failure in practice, that of integrated AC chargers.

6.3. Appreciating the Complexity of Users

There is still very little research insight into consumer aspects of VGI. In most VGI modeling studies (as noted in **Table 3**), there is typically an assumed number of PEVs that all participate in a VGI program, with PEVs charging either according to an assumed schedule (e.g., 14), to optimize grid operations (e.g., 141), or to minimize the charging cost for individual PEV owners (e.g., 142). One study explicitly addressed the question for Mainstream buyers, but that study presented the VGI case as requiring the PEV driver stay plugged in a contracted number of hours (not actually needed or used in actual GIV businesses), finding that few buyers would participate if a fixed number of hours were required and suggesting reward for more, rather than a set minimum, might lead to higher VGI participation (90). In most studies, PEV buyers and drivers are either not explicitly considered or modeled at all, or they are all assumed to behave in a way that optimizes an entire system, or that maximizes their own financial benefits (or minimizes total cost of operation).

However, consumer perceptions and motivations are typically more sophisticated and varied than those of an optimizing agent. Although there are many behavioral theories to draw from (143, 144), here we provide the illustrative examples of Axsen and Kurani's framework that was first developed to categorize consumer perceptions of PEVs according to two dimensions (145, 146). First is functional and symbolic, where PEVs and VGI technology can provide functional benefits such as cost savings as well as symbolic benefits, such as communicating that the consumer is green or conscious of the environment. Second is the private versus societal dimension; private benefits are realized by the consumer only (as with the previous two examples), whereas societal benefits are realized by society more generally, e.g., through reductions in GHG

TRANSFORMATIVE FAILURES IN PRACTICE: THE CASE OF ALTERNATING CURRENT CHARGERS

As one example of a directionality failure, most automobile original equipment manufacturers (OEMs) have installed relatively simple, low-power alternating current (AC) chargers on the vehicles, and left to regional companies the task of designing and paying for duplicative charging equipment on the ground for fast charging through a new direct current (DC) port. The alternative is to enlarge the AC charger, or to use the drive electronics also for high-power AC charging. The latter path has been taken by manufacturers of the Renault ZOE, the MiniE, and the standard charger on the BMW i3 as well as by truck and bus manufacturer suppliers such as the 70 kW EPC Power integrated charging system.

The integrated charger-drive system is surprisingly lower cost. For example, the Renault ZOE achieves a 44 kW AC charge rate by adding ~350 € of parts to the car (139). To provide the same amount of power from an external charger now costs in the 5,000–20,000 € range—more than a ten-to-one cost inflation to duplicate the charger functions off-board. But most OEMs do not take the low-cost approach, instead providing a DC port and requiring a second off-board AC-to-DC charger. Such gross cost inefficiency would not be possible except that the automotive industry considers the external charger to not be part of the automotive system.

So, if a few automobile OEMs are taking the on-board, AC, integrated solution, why do most not do so? In discussions with many such companies, some see this as a second stage they will reach after getting more familiar with electric vehicle designs, others see it as too complex and requiring too many certifications, and some cite regional electric differences (in grid phase and voltage). As a comparison case, for the Toyota Hybrid System first used in the 1997 Prius, "Eighty of Toyota's best research engineers spent two years" (140), a $4.5 billion R&D effort by Toyota. At vastly lower cost, an integrated charger and motor drive has been designed, tested, and produced by at least three independent teams, each with a handful of engineers (1–5) working less than 3 years (AC Propulsion for BMW, EPC Power, and Continental for Renault). Automaker willingness to spend lavishly on the hybrid gasoline-electric drive may be because it is primarily a mechanical engineering problem (a challenging problem but in a familiar discipline), whereas the integrated motor-drive-charger is a cutting-edge problem in power electronics engineering (new to automakers), and in regional electrical standards (totally foreign to automakers). Until more than a couple of OEMs solve this problem in the more cost-efficient way, the PEV industry is left only one choice for en-route charging—DC charging that is very expensive both to install and to maintain, resulting in a struggle to find viable business models for en-route charging station network providers. In addition to the challenge of expensive en-route charging, this failure significantly affects V2G because revenue is proportional to power, so low-cost but high-power chargers in PEVs would enable higher-value grid services at lower capital cost to the vehicle owner.

emissions, air pollution, or oil reliance. Axsen and Kurani distinguish between two types of societal frames summarized in **Table 6**. Functional-societal frames relate the vehicle's direct impacts on the environment, energy security, or land-use patterns. In contrast, symbolic-societal frames relate the vehicle's ability to inspire other users, companies, and governments to engage in activities that in turn impact society more broadly, which could maintain or strengthen existing negative impacts (e.g., supporting current gasoline use) or reverse them (e.g., transition to low-carbon fuels) (146, 147). Due to these complex dynamics, passenger vehicles can be perceived as mixed goods that have aspects of private and public dimensions, especially for alternative fuel vehicles and transportation practices where reduced environmental impact is often the primary rationale for development (148). The framework is a useful way to collect a wide variety of consumer perceptions relating to VGI—rather than assuming that all PEV owners are optimizing their behavior solely based on functional-private motivation, for example, cost savings (149).

Table 6 Functional-symbolic and private-societal dimensions of driver behavior[a]

	Functional	Symbolic
Private	What it does for you (e.g.,) ■ helps you save money ■ is reliable ■ allows one to have fun while driving (experiential)	What it represents (e.g.,) ■ self-identity ■ personal status ■ group membership
Societal	What it does for society (e.g.,) ■ reduces air pollution ■ reduces global warming ■ reduces oil use	What it says to society (e.g.,) ■ Inspires other consumers ■ Sends message to automakers, government, oil companies

[a]Table adapted from Reference 149.

Furthermore, the few studies that focus on consumer aspects of VGI tend to rely on survey techniques including stated choice experiments, as well as a few cases that utilize interviews or focus groups. In such studies, one must consider the nature of the participant sample, including the representativeness of the sample, the country of focus, and whether the target population comprises current owners of PEVs or "Pioneers" or more "Mainstream" car buyers. On the latter point, PEV Pioneers have been found to have different motivations and preferences from larger populations of new vehicle buying households including the potential "next" or "early Mainstream" PEV buyers (20). Thus, it seems wise for future research of potential large-scale VGI systems to include data collection from more Mainstream car buyers.

6.4. Toward Interdisciplinary, Multi-Method Modeling Approaches

A final gap and potential priority for future VGI research is to move toward interdisciplinary and multi-method efforts. In our sociotechnical summary in this review, few studies reveal insights that cross more than one or two of the four categories we identify: technical, financial, socio-environmental and individual/behavioral. The most common linkages are between technical and financial dimensions, or techno-economic assessments of VGI. Almost no studies explicitly include both sophisticated behavioral models as well as techno-economic or environmental models. As previously noted, VGI modeling studies tend to be based on a single modeling type and discipline (economic and/or technical optimization) and to make exogenous assumptions about the consumer, including PEV adoption rates, PEV usage patterns, and PEV owner participation rates in VGI—usually with little or no empirical data to support these assumptions.

In part, greater integration (and insight) could occur through multi-method approaches. For example, although VGI modeling efforts are dominated by optimization models, "simulation" energy-economy models can instead be used to represent what consumers and stakeholders may actually do in a given policy context, given their preferences and perceptions (150). Even more novel is to develop studies that directly integrate empirical data from surveys and interviews (as noted in the previous section) with models of VGI participation that in turn simulate the technical, economic, and environmental impacts of such systems. For example, the seventh study in **Table 3** (see far right column) includes consumer-informed and endogenous representations of PEV purchase behavior and VGI participation, in tandem with an optimization model to represent the electrical grid (M. Wolinetz, J. Axsen, J. Peters & C. Crawford, manuscript under review). A study approach that also adds in a higher-level, institutional component to represent the system-level transformative failures that act as barriers to a VGI transition would be most comprehensive.

7. IMPLICATIONS AND CONCLUSIONS

To conclude, a VGI transition has much to offer society. It compellingly transforms vehicles from the heart of transport problems to part of the solution. The transition could empower vehicles to simultaneously improve the efficiency (and profitability) of electricity grids, reduce GHG emissions, accommodate low-carbon sources of energy, and reap cost savings for owners, drivers, and other users. However, such a transition is not effortless—it must confront an array of obstacles cutting across technical dimensions such as batteries and communication systems, financial ones such as purchase price and first-cost, negative environmental externalities, and behavioral challenges including notions of inconvenience, trust, confusion, and range anxiety. Also, the net impacts of a VGI system may depend on which objectives are prioritized; for example, there is no guarantee that a cost-minimizing VGI system will lower environmental impacts—especially if negative environmental externalities are still unaddressed by policy.

Therefore, when we think about the future promise of a VGI transition, we need to focus beyond batteries, vehicles and power plants to the whole sociotechnical system. We recommend a sociotechnical system focus, as both a unit of analysis and analytical tool as well as a practical matter of designing policy or behavioral change; for only an alignment of technical, economic, political, and social conditions resulted in the acceptance of the gasoline car. This implies that efforts to alter modern modes of transportation must not only respond to technical challenges, but must also create proper economic incentives, engender political support, and shape social and cultural attitudes. A sociotechnical heuristic also offers a subtle but strong critique to much of the techno-economic work done so far, given this paradigm presumes that individuals will make the same rational decisions as the modeled optimizing agents (151). History teaches us that policies attempting only to overcome technical or social barriers—such as merely developing a better engine or educating automobile drivers about other options—will not work. We must broaden the research agenda for VGI so that we explore a greater number of cases, overcome transformative failures, appreciate the complexity of users, and embrace interdisciplinary and mixed-methods approaches.

More broadly, if one accepts that automobiles are chosen for reasons extending beyond the "rational" or "technical," then transportation R&D pathways aimed at promoting new modes of transport must drastically change. Despite the billions of dollars in research and development, procurement, tax incentives, tax credits, subsidies, standards, and financial assistance, the impediments to more sustainable forms of transport remain at least partly social and cultural. Until these remaining cultural barriers are targeted in the same way that engineers and scientists tackle technical impediments, the promise of new energy or transport systems—such as widespread, societally beneficial VGI programs—will remain unfulfilled. Consumer attitudes, values, and expectations are just as important as better technology in determining why consumers may embrace PEVs and why they will or will not participate in VGI services.

DISCLOSURE STATEMENT

B.K.S. and J.A. are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review. W.K. has a financial interest in a startup company that is establishing businesses to provide grid services from EVs.

ACKNOWLEDGMENTS

The authors are appreciative of the Research Councils United Kingdom (RCUK) Energy Program Grant EP/K011790/1 "Center on Innovation and Energy Demand," the Danish Council for Independent Research (DFF) Sapere Aude Grant 4182-00033B "Societal Implications of a Vehicle-to-Grid Transition in Northern Europe," which have supported elements of the work reported here. Thanks also to Michael Wolinetz for contributing to our review of the VGI modeling literature. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the RCUK Energy Program or the DFF.

LITERATURE CITED

1. IEA. 2015. *Energy and Climate Change: World Energy Outlook Special Report*. Paris: OECD (Org. Econ. Co-op. Dev.)/IEA (Int. Energy Agency)
2. Williams J, DeBenedictis A, Ghanadan R, Mahone A, Moore J, Morrow WR II. 2012. The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. *Science* 335(6):53–59
3. Kempton W, Tomic J, Letendre S, Brooks A, Lipman T. 2001. *Vehicle-to-grid power: battery, hybrid, and fuel cell vehicles as resources for distributed electric power in California*. Rep. IUCD-ITS-RR-01–03, Inst. Transport. Stud., Davis, CA
4. Kempton W. 2012. *Hierarchical priority and control algorithms for the grid-integrated vehicle*. US Patent No. 8116915
5. California Independent System Operator. 2014. *California Vehicle-Grid Integration (VGI) Roadmap: Enabling Vehicle-Based Grid Services*. Sacramento, CA: CAISO
6. Sovacool BK, Hirsh RF. 2009. Beyond batteries: an examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. *Energy Policy* 37(3):1095–103
7. Kempton W, Letendre SE. 1997. Electric vehicles as a new power source for electric utilities. *Transport. Res. D* 2(3):157–75
8. Letendre SE, Kempton W. 2002. The V2G concept: a new model for power? *Public Utilities Fortnightly* Febr. 15. **http://www1.udel.edu/V2G/docs/V2G-PUF-LetendKemp2002.pdf**
9. Peng M, Liu L, Jiang C. 2012. A review on the economic dispatch and risk management of the large-scale plug-in electric vehicles (PHEVs)-penetrated power systems. *Renew. Sustain. Energy Rev.* 16(3):1508–15
10. Hajimiragha A, Canizares CA, Fowler MW. 2010. Optimal transition to plug-in hybrid electric vehicles in Ontario, Canada, considering the electricity-grid limitations. *IEEE Trans. Ind. Electron.* 57(2):690–701
11. Madzharov D, Delarue E, D'Haeseleer W. 2014. Integrating electric vehicles as flexible load in unit commitment modeling. *Energy* 65:285–94
12. Abdulkadir B, Ogden JM, Yang C. 2015. *Quantifying the economic value of vehicle-grid integration: a case study of dynamic pricing in the Sacramento Municipal Utility District*. Rep., Inst. Transport. Stud., Univ. Calif., Davis
13. Kempton W, Tomić J. 2005. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. *J. Power Sources* 144:280–94
14. Lund H, Kempton W. 2008. Integration of renewable energy into the transport and electricity sectors through V2G. *Energy Policy* 36(9):3578–87
15. Dallinger D, Gerda S, Wietschel M. 2013. Integration of intermittent renewable power supply using grid-connected vehicles—a 2030 case study for California and Germany. *Appl. Energy* 104:666–82
16. Tomić J, Kempton W. 2007. Using fleets of electric-drive vehicles for grid support. *J. Power Sources* 168:459–68
17. Sioshansi R, Denholm P. 2010. The value of plug-in hybrid electric vehicles as grid resources. *Energy J.* 31(3):1–23
18. Steinhilber S, Wells P, Thankappan S. 2013. Socio-technical inertia: understanding the barriers to electric vehicles. *Energy Policy* 60:531–39
19. Sovacool BK. 2011. The interpretive flexibility of oil and gas pipelines: case studies from Southeast Asia and the Caspian Sea. *Technol. Forecast. Soc. Change* 78(4):610–20
20. Axsen J, Goldberg S, Bailey J. 2016. How might potential future plug-in electric vehicle buyers differ from current "Pioneer" owners? *Transport. Res. D* 47:357–70

21. Axsen J, Kurani KS. 2013. Hybrid, plug-in hybrid or electric: What do car buyers want? *Energy Policy* 61:532–43
22. Carley S, Krause RM, Lane BW, Graham JD. 2013. Intent to purchase a plug-in electric vehicle: a survey of early impressions in large US cites. *Transport. Res. D* 18:39–45
23. Wolinetz M, Axsen J. 2017. How policy can build the plug-in electric vehicle market: insights from the REspondent-based Preference And Constraints (REPAC) model. *Technol. Forecast. Soc. Change* 117:238–50
24. *EV-Volumes.com.* 2017. The Electric Vehicle World Sales Database. **http://www.ev-volumes.com/country/total-world-plug-in-vehicle-volumes/**
25. Dijk M, Orsato RJ, Kemp R. 2013. The emergence of an electric mobility trajectory. *Energy Policy* 52:135–45
26. Hein R, Kleindorfer PR, Spinler S. 2012. Valuation of electric vehicle batteries in vehicle-to-grid and battery-to-grid systems. *Technol. Forecast. Soc. Change* 79:1654–71
27. Galus MD, Zima M, Andersson G. 2010. On integration of plug-in hybrid electric vehicles into existing power system structures. *Energy Policy* 38:6736–45
28. Kley F, Lerch C, Dallinger D. 2011. New business models for electric cars—a holistic approach. *Energy Policy* 39:3392–403
29. Kempton W, Marra F, Bach Andersen P, Garcia-Valle R. 2013. Business models and control and management architectures for EV electrical grid integration. In *Power Electronics and Power Systems*, Vol. 2: *Electric Vehicle Integration into Modern Power Networks*, ed. R Garcia-Valle, J Peças Lopes, pp. 87–105. New York: Springer
30. Langton A, Crisostomo N. 2014. *Vehicle-grid integration: a vision for zero-emission transportation interconnected throughout California's electricity system*. Rep. R-13-11-007, Calif. Public Utilities Comm., San Franc.
31. Thingvad A, Martinenas S, Bach Andersen P, Marinelli M, Christensen BE, Oleson OJ. 2016. Economic comparison of electric vehicles performing unidirectional and bidirectional frequency control in Denmark with practical validation. *Proc. Int. Univ. Power Eng. Conf. (UPEC)*, *51th*, *Coimbra*, *Port.*, *Sep 6–9*, pp. 1–6. Piscataway Township, NJ: Inst. Electr. Electr. Eng.
32. Wald ML. 2013. In two-way charging, electric cars begin to earn money from the grid. *New York Times*, April 25. **http://www.nytimes.com/2013/04/26/business/energy-environment/electric-vehicles-begin-to-earn-money-from-the-grid.html**
33. Bailey J, Axsen J. 2015. Anticipating PEV buyers' acceptance of utility controlled charging. *Transport. Res. A* 82:29–46
34. Kempton W, Tomic J. 2005. Vehicle-to-grid power fundamentals: calculating capacity and net revenue. *J. Power Sources* 144:268–79
35. Hidrue MK, Parsons GR. 2015. Is there a near-term market for vehicle-to-grid electric vehicles? *Appl. Energy* 151:67–76
36. Guille C, Gross G. 2009. A conceptual framework for the vehicle-to-grid (V2G) implementation. *Energy Policy* 37:4379–90
37. Yamagata Y, Seya H, Kuroda S. 2014. Energy resilient smart community: sharing green electricity using V2C technology. *Energy Procedia* 61:84–87
38. Hosseini SS, Badri A, Parvania M. 2014. A survey on mobile energy storage systems (MESS): applications, challenges and solutions. *Renew. Sustain. Energy Rev.* 40:161–70
39. Deleted in proof
40. Debnath UK, Ahmad I, Habibi D. 2014. Quantifying economic benefits of second life batteries of gridable vehicles in the smart grid. *Electr. Power Energy Syst.* 63:577–87
41. Arslan O, Karasan OK. 2013. Cost and emission impacts of virtual power plant formation in plug-in hybrid electric vehicle penetrated networks. *Energy* 60:116–24
42. Saber AY, Venayagamoorthy GK. 2010. Intelligent unit commitment with vehicle-to-grid—a cost-emission optimization. *J. Power Sources* 195:898–911
43. Habib S, Kamran M, Rashid U. 2015. Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks—a review. *J. Power Sources* 277:205–14

44. Hughes TP. 1983. *Networks of Power: Electrification in Western Society, 1880–1930*. Baltimore: Johns Hopkins Univ. Press
45. Hughes TP. 1987. The evolution of large technological systems. In *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. WE Bijker, TP Hughes, TJ Pinch, pp. 51–82. Cambridge, MA: MIT Press
46. Geels FW. 2005. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). *Technol. Anal. Strateg. Manag.* 17(4):445–76
47. Pasaoglu G, Fiorello D, Martino A, Zani L, Zubaryeva A, Thiel C. 2014. Travel patterns and the potential use of electric cars—results from a direct survey in six European countries. *Technol. Forecast. Soc. Change* 87:51–59
48. Faruqui A, Hledik R, Newell S, Pfeifenberger H. 2007. The power of 5 percent. *Electr. J.* 20:68–77
49. Kintner-Meyer M, Schneider K, Pratt R. 2007. *Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids*, Part 1: *technical analysis*. Rep., Pac. Northwest Nat. Lab., Richland, WA. **http://www.pnl.gov/energy/eed/etd/pdfs/phev_feasibility_analysis_combined.pdf**
50. Denholm P, Short W. 2006. *An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles*. Tech. Rep. NREL/TP-620-40293, Nat. Renew. Energy Lab., Washington, DC
51. National Research Council. 2010. *Transitions to Alternative Transportation Technologies—Plug-in Hybrid Electric Vehicles*. Washington, DC: Nat. Acad. Press
52. Saxena S, MacDonald J, Moura S. 2015. Charging ahead on the transition to electric vehicles with standard 120 V wall outlets. *Appl. Energy* 157:720–28
53. Needell ZA, McNerney J, Chang MT, Trancik JE. 2016. Potential for widespread electrification of personal vehicle travel in the United States. *Nat. Energy* 1:16112
54. Pearre NS, Kempton W, Guensler RL, Elango VV. 2011. Electric vehicles: How much range is required for a day's driving? *Transport. Res. C* 19(6):1171–84
55. Kempton W. 2016. Electric vehicles: driving range. *Nat. Energy* 1:16131
56. Loisel R, Pasaoglu G, Thiel C. 2014. Large-scale deployment of electric vehicles in Germany by 2030: an analysis of grid-to-vehicle and vehicle-to-grid concepts. *Energy Policy* 65:432–43
57. US Department of Energy (DOE), US Energy Information Administration. 2013. *Updated capital cost estimates for electricity generation plants, November 2010 U.S. Energy Information Administration*. Rep., Washington, DC
58. Bureau of Transportation Statistics. 2016. *National Transportation Statistics 2016*. Washington, DC: US Dep. Transport.
59. US Environmental Protection Agency (EPA). 2016. *Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2016*. EPA Tech. Rep. EPA-420-R-16-010, Washington, DC
60. Richardson DB. 2013. Electric vehicles and the electric grid: a review of modeling approaches, impacts, and renewable energy integration. *Renew. Sustain. Energy Rev.* 19:247–54
61. Dallinger D, Wietschel M. 2012. Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. *Renew. Sustain. Energy Rev.* 16(5):3370–82
62. Lyon TP, Michelin M, Jongejan A, Leahy T. 2012. Is "smart charging" policy for electric vehicles worthwhile? *Energy Policy* 41:259–68
63. Hidrue MK, Parsons GR. 2015. Is there a near-term market for vehicle-to-grid electric vehicles? *Appl. Energy* 151:67–76
64. Noel L, McCormack R. 2014. A cost benefit analysis of a V2G-capable electric school bus compared to a traditional diesel school bus. *Appl. Energy* 126:246–65
65. De Losi Rios A, Goentzel J, Nordstorm KE, Siegert CW. 2012. Economic analysis of vehicle-to-grid (V2G)-enabled fleets participating in the regulation service market. In *Innovative Smart Grid Technologies (ISGT); IEEE PES*. Washington, DC: IEEE. **http://ieeexplore.ieee.org/abstract/document/6175658/?reload=true**
66. Scott MJ, Kintner-Meyer M, Elliott DB, Warwick WM. 2007. *Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids*, Part 2: *economic assessment*. Rep., Pac. Northwest Nat. Lab., Richland, WA. **http://www.pnl.gov/energy/eed/etd/pdfs/phev_feasibility_analysis_combined.pdf**

67. Ensslen A, Ringler P, Jochem P, Keles D, Fichtner W. 2014. About business model specifications of a smart charging manager to integrate electric vehicles into the German electricity market. In *14th IAEE European Conference*. Cleveland: IAEE
68. Li Y, Zhan C, de Jong M, Lukszo Z. 2016. Business innovation and government regulation for the promotion of electric vehicle use: lessons from Shenzhen. *China J. Cleaner Prod.* 134(Part A):371–83
69. Will C, Schuller A. 2016. Understanding user acceptance factors of electric vehicle smart charging. *Transp. Res. C* 71:198–214
70. Brandt T, Wagner S, Neumann D. 2017. Evaluating a business model for vehicle-grid integration: evidence from Germany. *Transport. Res. D* 50:488–504
71. Kutscher CF. 2007. *Tackling Climate Change in the U.S.: Potential Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030*. Washington, DC: Am. Solar Energy Soc.
72. Addison D, Al-Chalabi M, Elwell C, Evans M, Salmond N, Saunders R, 2010. *Open Roads, Anxious Drivers: A Technology and Policy Assessment for Long Range Electric Vehicles in the United Kingdom*. London: Energy Policy Proj.
73. Bradley TH, Frank AA. 2009. Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. *Renew. Sustain. Energy Rev.* 13(1):115–28
74. Samaras C, Meisterling K. 2008. Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy. *Environ. Sci. Technol.* 42:3170–76
75. Stephan CH, Sullivan J. 2008. Environmental and energy implications of plug-in hybrid electric vehicles. *Environ. Sci. Technol.* 42:1185–90
76. IEA. 2010. *Energy Technology Perspectives: Scenarios and Strategies to 2050*. Paris: Int. Energy Agency. **https://www.iea.org/publications/freepublications/publication/etp2010.pdf**
77. Tessum C, Hill J, Marshall J. 2014. Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proc. Natl. Acad. Sci.* 111(52):18490–95
78. Ji S, Cherry CR, Bechle MJ, Wu Y, Marshall JD. 2012. Electric vehicles in China: emissions and health impacts. *Environ. Sci. Technol.* 46(4):2018–24
79. Raykin L, MacLean HL, Roorda MJ. 2012. Implications of driving patterns on well-to-wheel performance of plug-in hybrid electric vehicles. *Environ. Sci. Technol.* 46:6363–70
80. Sioshansi R, Denholm P. 2009. Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services. *Environ. Sci. Technol.* 43:1199–204
81. Ekman CK. 2011. On the synergy between large electric vehicle fleet and high wind penetration—an analysis of the Danish case. *Renew. Energy* 36:546–53
82. Jian L, Zheng Y, Xiao X, Chan CC. 2015. Optimal scheduling for vehicle-to-grid operation with stochastic connection of plug-in electric vehicles to smart grid. *Appl. Energy* 146:150–61
83. Jadhav HT, Roy R. 2015. Stochastic optimal power flow incorporating offshore wind farm and electric vehicles. *Electr. Power Energy Syst.* 69:173–87
84. Lund PD, Lindgren J, Mikkola J, Salpakari J. 2015. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew. Sustain. Energy Rev.* 45:785–807
85. Waraich RA, Galus MD, Doler C, Balmer M, Andersson G, et al. 2013. Plug-in hybrid electric vehicles and smart grids: investigations based on a microsimulation. *Transport. Res. C* 28:74–86
86. Hennings W, Mischinger S, Linssen J. 2013. Utilization of excess wind power in electric vehicles. *Energy Policy* 62:139–44
87. Fattori F, Anglani N, Mulierre G. 2014. Combining photovoltaic energy with electric vehicles, smart charging and vehicle-to-grid. *Solar Energy* 110:438–51
88. van der Kam M, van Sark W. 2015. Smart charging of electric vehicles with photovoltaic power and vehicle-to-grid technology in a microgrid; a case study. *Appl. Energy* 152:20–30
89. Denholm P, Kulcinski GL, Hollway T. 2005. Emissions and energy efficiency assessment of baseload wind energy systems. *Environ. Sci. Technol.* 39:1903–11
90. Parsons GR, Hidrue MK, Kempton W, Gardner MP. 2014. Willingness to pay for vehicle-to-grid (V2G) electric vehicles and their contract terms. *Energy Econ.* 42:313–24
91. Bailey J, Axsen J. 2015. Anticipating PEV buyers' acceptance of utility controlled charging. *Transport. Res. A* 82:29–46

92. Axsen J, Kurani KS. 2013. Connecting plug-in vehicles with green electricity through consumer demand. *Environ. Res. Lett.* 8(1):1–8
93. Bailey J, Axsen J. 2015. Anticipating PEV buyers' acceptance of utility controlled charging. *Transport. Res. A: Policy Pract.* 82:29–46
94. Hidrue MK, Parsons GR. 2015. Is there a near-term market for vehicle-to-grid electric vehicles? *Appl. Energy* 151:67–76
95. Deleted in proof
96. Ota Y, Taniguchi H, Baba J, Yokohama A. 2015. Implementation of autonomous distributed V2G to electric vehicle and DC charging system. *Electric Power Syst. Res.* 120:177–83
97. Zhong J, He L, Li C, Cao Y, Wang J, et al. 2014. Coordinated control for large-scale EV charging facilities and energy storage devices participating in frequency regulation. *Appl. Energy* 123:253–62
98. Khayyam H, Ranjbarzadeh H, Marano V. 2012. Intelligent control of vehicle to grid power. *J. Power Sources* 201:1–9
99. Battistelli C, Baringo L, Conejo AJ. 2012. Optimal energy management of small electric energy systems including V2G facilities and renewable energy sources. *Electric Power Syst. Res.* 92:50–59
100. López MA, Martin S, Aguado JA, de la Torre S. 2013. V2G strategies for congestion management in microgrids with high penetration of electric vehicles. *Electric Power Syst. Res.* 104:28–34
101. Sun Y, Liu W, Su M, Li X, Wang H, et al. 2014. A unified modeling and control of a multi-functional current source-typed converter for V2G application. *Electric Power Syst. Res.* 106:12–20
102. Haddadian G, Khalili N, Khodayar M, Shahidehpour M. 2015. Optimal scheduling of distributed battery storage for enhancing the security and the economics of electric power systems with emission constraints. *Electric Power Syst. Res.* 124:152–59
103. Green RC II, Wang L, Alam M. 2011. The impact of plug-in hybrid electric vehicles on distribution networks: a review and outlook. *Renew. Sustain. Energy Rev.* 15:544–53
104. Wang W, Coignard J, Zeng T, Zhang C, Saxena S. 2016. Quantifying electric vehicle battery degradation from driving versus vehicle-to-grid services. *J. Power Sources* 332:193–203
105. Shinzaki S, Sadano H, Maruyama Y, Kempton W. 2015. *Deployment of vehicle-to-grid technology and related issues*. Congr. Pap. 2015-01-0306, SAE Int., Warrendale, PA
106. McPhail D. 2014. Evaluation of ground energy storage assisted electric vehicle DC fast charger for demand charge reduction and providing demand response. *Renew. Energy* 67:103–8
107. Peterson SB, Apt J, Whitacre JF. 2010. Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. *J. Power Sources* 195:2385–92
108. Bishop JDK, Axon CJ, Bonilla D, Tran M, Banister D, et al. 2013. Evaluating the impact of V2G services on the degradation of batteries in PHEV and EV. *Appl. Energy* 111:206–18
109. Marongiu A, Roscher M, Sauer DU. 2015. Influence of the vehicle-to-grid strategy on the aging behavior of lithium battery electric vehicles. *Appl. Energy* 137:899–912
110. Juul N. 2012. Battery prices and capacity sensitivity: electric drive vehicles. *Energy* 47:403–10
111. Neubauer J, Brooker A, Wood E. 2012. Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies. *J. Power Sources* 209:269–77
112. Saxena S, Floch CL, MacDonald J, Moura S. 2015. Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models. *J. Power Sources* 282:265–76
113. Greene DL, German J, Delucchi MA. 2007. *Fuel Economy: The Case for Market Failure*. Knoxville, TN: Oak Ridge Nat. Lab./Nat. Transport. Res. Cent.
114. Turrentine TS, Kurani KS. 2007. Car buyers and fuel economy? *Energy Policy* 35:1213–23
115. Geller H, Attali S. 2005. *The Experience with Energy Efficiency Policies and Programs in IEA Countries*. Paris: Int. Energy Agency
116. King CW, Webber M. 2008. The water intensity of the plugged-in automotive economy. *Environ. Sci. Technol.* 42:4305–11
117. Gleeson T, Wada Y, Bierkens MFP, van Beek LPH. 2012. Water balance of global aquifers revealed by groundwater footprint. *Nature* 488:197–200
118. Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. 2012. Comparative environmental life cycle assessment of conventional and electric vehicles. *J. Ind. Ecol.* 17(1):53–64

119. Ramoni MO, Zhang H-C. 2013. End-of-life (EOL) issues and options for electric vehicle batteries. *Clean Technol. Environ. Policy* 15:881–91
120. Noel L, Brodie JF, Kempton W, Archer CL, Budischak C. 2017. Cost minimization of generation, storage, and new loads, comparing costs with and without externalities. *Appl. Energy* 189:110–21
121. Noel L. 2017. The hidden economic benefits of large-scale renewable energy deployment: integrating heat, electricity and vehicle systems. *Energy Res. Soc. Sci.* 26:54–59
122. Bailey J, Axsen J. 2015. Anticipating PEV buyers' acceptance of utility controlled charging. *Transport. Res. A* 82:29–46
123. Axsen J, Goldberg S, Bailey J, Kamiya G, Langman B, et al. 2015. *Electrifying vehicles: insights from the Canadian plug-in electric vehicle study*. Rep., Sustain. Transport. Res., Simon Fraser Univ., Vancouver, BC
124. Franke T, Krems JF. 2013. Interacting with limited mobility resources: psychological range levels in electric vehicle use. *Transport. Res. A* 48:109–22
125. Franke T, Neumann I, Bühler F, Cocron P, Krems JF. 2012. Experiencing range in an electric vehicle: understanding psychological barriers. *Appl. Psychol.: Int. Rev.* 61:368–91
126. Egbue O, Long S. 2012. Barriers to widespread adoption of electric vehicles: an analysis of consumer attitudes and perceptions. *Energy Policy* 48:717–29
127. Tran M, Banister D, Bishop JDK, McCulloch MD. 2012. Realizing the electric-vehicle revolution. *Nat. Clim. Change* 2:328–33
128. Kurani KS, Turrentine T, Sperling D. 1994. Demand for electric vehicles in hybrid households: an exploratory analysis. *Transp. Policy* 1(4):244–56
129. Bailey J, Axsen J. 2015. Anticipating PEV buyers' acceptance of utility controlled charging. *Transport. Res. A* 82:29–46
130. Axsen J, Langman B, Goldberg S. 2017. Confusion of innovations: Mainstream consumer perceptions and misperceptions of electric-drive vehicles and charging programs in Canada. *Energy Res. Soc. Sci.* 27:163–73
131. Renault Nissan Alliance. 2015. Power to spare—Nisssan and Endesa sign pledge to promote Europe's first mass market vehicle to grid system. *Renault Nissan*, May 18. **http://blog.alliance-renault-nissan.com/category/tag/v2g**
132. Oliver GH, Kitirattragarn V. 2008. Taxi owners' buying preferences of hybrid-electric vehicles and their implications for emissions in New York City. *Transport. Res. A* 42:1064–73
133. Matthews L, Lynes J, Riemer M, Del Matto T, Cloet N. 2017. Do we have a car for you? Encouraging the uptake of electric vehicles at point of sale. *Energy Policy* 100:79–88
134. Cahill E, Davies-Shawhyde J, Turrentine T. 2014. *New car dealers and retail innovation in California's plug-in electric vehicle market*. Work. Pap. UCD-ITSL, Inst. Transport. Stud., Univ. California, Davis
135. Barmore C. 2013–2014. Tesla unplugged: automobile franchise laws and the threat to the electric vehicle market. *Va. J. Law Technol.* 18(2):186–228
136. Melton N, Axsen J, Sperling D. 2016. Moving beyond alternative fuel hype to decarbonize transportation. *Nat. Energy* 3:16013
137. Weber KM, Rohracher H. 2012. Legitimizing research, technology and innovation policies for transformative change: combining insights from innovation systems and multi-level perspective in a comprehensive "failures" framework. *Res. Policy* 41(6):1037–47
138. Azar C, Sandén BA. 2011. The elusive quest for technology-neutral policies. *Environ. Innov. Soc. Trans.* 1(1):135–39
139. Vignaud A, Fennel H. 2012. *Efficient electric powertrain with externally excited synchronous machine without rare earth magnets, using the example of the Renault system solution*. Conf. Pap., 33rd Int. Vienna Motor Symp., Vienna
140. Sherman D. 2017. What came before: the real history of the Toyota Prius. *Car and Driver*, April. **http://www.caranddriver.com/flipbook/what-came-before-the-real-history-of-the-toyota-prius**
141. Weis A, Jaramillo P, Michalek J. 2014. Estimating the potential of controlled plug-in hybrid electric vehicle charging to reduce operational and capacity expansion costs for electric power systems with high wind penetration. *Appl. Energy* 115:190–204
142. Druitt J, Früh W-G. 2012. Simulation of demand management and grid balancing with electric vehicles. *J. Power Sources* 216:104–16

143. Jackson T. 2005. *Motivating sustainable consumption: a review of evidence on consumer behaviour and behavioural change*. Rep., Sustain. Dev. Res. Netw., Univ. Surrey, Guildford, UK. **http://www.sustainablelifestyles.ac.uk/sites/default/files/motivating_sc_final.pdf**
144. Sovacool BK. 2017. Experts, theories, and electric mobility transitions: toward an integrated conceptual framework for the adoption of electric vehicles. *Energy Res. Soc. Sci.* 27:78–95
145. Axsen J, Kurani KS. 2012. Interpersonal influence within car buyers' social networks: applying five perspectives to plug-in hybrid vehicle drivers. *Environ. Plann. A* 44(5):1057–65
146. Axsen J, Orlebar C, Skippon S. 2013. Social influence and consumer preference formation for pro-environmental technology: the case of a U.K. workplace electric-vehicle study. *Ecol. Econ.* 95(0):96–107
147. Noppers EH, Keizer K, Bolderdijk JW, Steg L. 2014. The adoption of sustainable innovations: driven by symbolic and environmental motives. *Glob. Environ. Change* 25:52–62
148. Brown MB. 2001. The civic shaping of technology: California's electric vehicle program. *Sci. Technol. Hum. Values* 26(1):56–81
149. Axsen J, Kurani KS. 2012. Interpersonal influence within car buyers' social networks: applying five perspectives to plug-in hybrid vehicle drivers. *Environ. Plann. A* 44:1057–65
150. Jaccard M, Loulou R, Kanudia A, Nyboer J, Bailie A, Labriet M. 2003. Methodological contrasts in costing greenhouse gas abatement policies: optimization and simulation modeling of micro-economic effects in Canada. *Eur. J. Oper. Res.* 145(1):148–64
151. Foulds C, Christensen TK. 2016. Funding pathways to a low-carbon transition. *Nat. Energy* 1:16087