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How to cite this publication
Please cite the final published version:

Citation:

Publication metadata

Title: The Future Promise of Vehicle-to-Grid (V2G) Integration: A Sociotechnical Review and Research Agenda
Author(s): Sovacool, BK, J Axsen, and W Kempton
Journal: Annual Review of Environment and Resources
DOI/Link: https://doi.org/10.1146/annurev-environ-030117-020220
Publication date: October 2017
Document version: Accepted manuscript (post-print)

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Tempering the Promise of Electric Mobility? A Sociotechnical Review and Research Agenda for Vehicle-Grid-Integration (VGI) and Vehicle-to-Grid (V2G)

Benjamin K. Sovacool\textsuperscript{12}, Jonn Axsen,\textsuperscript{3} and Willett Kempton\textsuperscript{4}

\textsuperscript{1} Aarhus University, Denmark  \textsuperscript{2} University of Sussex, United Kingdom  \textsuperscript{3} Simon Fraser University, Canada  \textsuperscript{4} University of Delaware, USA

Invited contribution for the 2017 Volume of \textit{Annual Review of Environment and Resources}

**Summary:** Vehicle-grid-integration (VGI) describes various approaches to link the electric power system and the transportation system in ways that may provide benefits to 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 pricing. VGI typically encompasses vehicle-to-grid (V2G), a more technically advanced vision with bidirectional flow of electricity between the vehicle and grid, in effect treating the PEV as storage device. Such VGI systems have the potential to help decarbonize transportation, support load balancing, integrate intermittent sources of 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, socioenvironmental, 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, and to provide additional rigor for continued technology-focused research. 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 almost zero studies address the need for institutional capacity and cross-sectoral policy coordination. This creates promising opportunities for future research.

**Acknowledgements:** The authors are appreciative to 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. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of RCUK Energy Program or the DFF.

**Keywords:** mobility; transportation; decarbonization pathways; electric mobility; vehicle-to-grid (V2G); Vehicle Grid Integration (VGI)

List of acronyms and abbreviations

$ -$ Denotes United States dollars unless otherwise noted
AC – Alternating Current
BEV – Battery Electric Vehicle
DC – Direct Current
Introduction

Globally, the transportation sector is rife with market failures—notably a continued reliance on 95% fossil fuel energy, and the resulting consequences for climate change, air pollution and other negative social impacts. Many researchers, policymakers and other stakeholders 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 concentrations at 450 ppm. Others similarly argue that penetration in that approximate range is necessary and/or likely based on present trends and technology improvement.

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), grid-integrated vehicles (GIV), or vehicle-grid-integration (VGI), overlapping concepts that 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. VGI is proposed as an overarching term, which includes systems that treat PEV 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 vehicle-to-grid (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. 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

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 allow greater utilization of existing generation capacity10 11 and of distribution infrastructure.12 For governments seeking to slash GHG emissions, VGI can help integrate intermittent renewable electricity generation into the grid13 by using renewable energy when it is available14 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, first cost 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 as well as teasing out 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.18 This perspective leads research managers (in government and in corporations) to pursue research activities in materials and processing, power electronics, low-cost and lightweight materials, and grid interaction. They have laid out a research program aimed at, for example, improving batteries’ conductivity and mechanical strength. The techno-economic adds 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.

In contrast, a sociotechnical perspective, as the name suggests, 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. 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.

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 over 15 years, add a battery and electric motor to a car that uses an internal combustion engine. HEVs use the electric motor and electronics to more efficiently operate the IC engine, which can cut fossil fuel usage, GHG emissions and air pollution. HEVs do not plug in to the electrical grid, while two types of plug-in electric vehicles (PEVs) do. First, plug-in hybrid electric vehicles (PHEVs) are capable recharging from the electrical grid, while maintaining an internal combustion engine that allows the flexibility to power the vehicle with fossil fuels or electricity. Second, battery electric vehicles (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, the limited sales volume of BEVs to date has been higher than sales of PHEVs globally (likely due in part to supply constraints), with about an even split in North America.

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, and tends to neglect to 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. Similarly, car-sharing programs may present unique opportunities for VGI.

The deployment of PEVs and VGI systems are particularly linked to recharge access, that is, the PEV driver’s access to technology that charges PEVs with grid electricity (see Text Box 1 for more on charging terminology). Technically, these devices are called Electric Vehicle Supply Equipment (EVSE) rather than chargers (because “chargers” convert AC to DC, which EVSEs for AC-charged vehicles do not)—however, in this paper we will use the more colloquial term charger or charging station. PEV drivers can potentially recharge at home, work, or other non-home destinations such as shopping malls (often called “public” charging, though this category typically includes privately owned charging stations that are non-home and non-workplace). PEV chargers also vary by the rate at which electricity can be put into the PEV battery, measured in kW.

**Text Box 1: 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 kW rating). This is far more driver-usable because the connector type tells the driver whether or not they can plug their car in to 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 US and Japan called “J1772”) Type 2 (rest of world), and, for DC charging, one of CHAdeMO, “Combo” or CCS. 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. The number of kWh 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 an 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, less time to wait.

2.2 VGI Concepts

As noted, vehicle-grid-integration (VGI) is a broad concept that describes efforts to intelligently link vehicles with the electric grid. California’s Independent System Operator, which created this term, provides several categorizations of the potential for VGI, where systems can vary by three attributes: i) whether benefits to the grid are provided by individual or aggregated resources, ii) whether actors have unified or fragmented objectives, and iii) the direction of power flow (unidirectional or bidirectional), (Table 1). First, aggregation refers to whether the PEVs involved in VGI are in a single location or are aggregated across a variety of locations. Second, the actors involved in VGI can be “unified”, meaning that the PEV drivers or operators are the same entity that is managing the charging for the electric utility, or “fragmented” if different entities are involved whom 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 the involved the aggregation of PEV users with fragmented objectives, e.g. PEV-owning households spread across a given region.

Table 1: Key Vehicle-Grid-Integration Concepts and Attributes

<table>
<thead>
<tr>
<th>VGI Concept</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power flow direction</td>
<td>Unidirectional: V1G, smart charging, controlled charging</td>
</tr>
<tr>
<td></td>
<td>Bi-directional: V2G</td>
</tr>
<tr>
<td>Aggregation of resources</td>
<td>Individual: one resource, or multiple resources in one location</td>
</tr>
<tr>
<td></td>
<td>Aggregated: multiple resources in multiple locations</td>
</tr>
<tr>
<td>Actor objectives</td>
<td>Unified: one actor, or multiple actors with aligned objectives</td>
</tr>
<tr>
<td></td>
<td>Fragmented: multiple actors with varying or conflicting objectives</td>
</tr>
<tr>
<td>Mechanism of actor engagement</td>
<td>Time-of-use pricing</td>
</tr>
<tr>
<td></td>
<td>Revenue sharing</td>
</tr>
<tr>
<td></td>
<td>Education or voluntarism</td>
</tr>
</tbody>
</table>

Source: Modified from 34. V2G = vehicle to grid.
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 may switch charging on or off. Bi-directional flow, called V2G (first proposed by 35), allows the PEV to both draw electricity from and provide electricity to the electricity grid, and requires a charger that requires more design analysis but typically little additional cost. Either managed charging or V2G can provide value to the grid, but if participating in electricity markets, one modeling effort concluded that V2G is on average thirteen times more valuable. 36 To date, most VGI literature has focused on the V2G concept, though 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 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 the user. 37 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. For example, cars in a trial program operated by University of Delaware and NRG EVs earned as much as $150/month (at the upper end of the range), of which half was provided to participating drivers. 38 A third mechanism of engagement is education and environmental value—the idea that informing the PEV operator that their participation in a VGI program can provide environmental benefits or enable more wind and solar might prompt some to enroll. Exploratory research suggests that about half of potential PEV buyers would consider enrolling in a VGI program if the only benefits offered were environmental. 39
Kempton and colleagues have developed a framework to explore V2G and identify 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 qualify to for fast-response markets, and provide auditability. Other phrases used to describe V2G concepts include V2X (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,” “battery-to-grid,” “gridable vehicles,” “virtual power plants,” and “S3Ps” (small portable power plants). In addition to the high-value regional markets mentioned above, a vehicle capable of V2G can, according to Habib et al, 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 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 argues that the generation, transmission and distribution of electricity occurs 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.” 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 focuses on the interrelationship of linkages between elements and co-evolutionary processes, with Figure 2 offering an illustration of the sociotechnical system surrounding modern car-based land transportation.56

**Figure 2: A sociotechnical system for personal automotive transportation**

![Socio-technical system for transportation diagram]

Source: 57

We apply a sociotechnical approach to the VGI concept more specifically by breaking down our analysis into four distinct categories summarized in Table 2. First comes technical or technological elements such as batteries and charging infrastructure, batteries and tires on vehicles, and interconnections to the electricity grid. Next is financial or 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 socioenvironmental, 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.
Table 2: Overview of Sociotechnical dimensions to a VGI Transition

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

In laying out the following sections, it is not our intent to suppose that demarcations between “technical,” “financial,” “socioenvironmental,” 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, since 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. Note that since Sovacool and Hirsh’s 2009 sociotechnical analysis of PEVs and V2G systems, no other VGI studies have taken an explicit sociotechnical approach.58 Here we draw from different studies that tend to focus on one or two aspects of this framework, where this Review in effect compiles 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, socioenvironmental, and consumer dimensions, each of which are 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, so 95% of the time, personal vehicles sit unused in parking lots or garages, typically near a building with electrical power. The first technical benefit is that VGI automobiles can turn unused equipment into useful services to the grid.

The second benefit derives from the fact that many utility resources go under-utilitized, an implication of the way that electric generation and transmission must 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 the nation’s vehicles at a much lower cost than typically gasoline or diesel prices. In the United States, for instance, 8 to 12 percent of peak electricity demand occurs within just 80 to 100 hours during the year. Because much of the generating capacity remains unused, one study estimate 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 if they drew power from the grid at off-peak times. Consequently, utility companies would earn extra revenues during these off-peak periods.

Denholm and Short also modeled addition of PHEVs to recorded utility loads and considered their impact for peaking generation and reserve capacity. Assuming a PHEV penetration of 50 percent 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, the 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.” More recently, Saxena et al. argue that since PEVs operate at higher efficiency than conventional ones, and seldom exceed 100 kilometers of daily travel, 85% to 89% of passenger vehicle drivers across the United States could be satisfied with EVs 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 and colleagues 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 many but not all daily driving; other studies assume a larger battery is required for most consumers, to meet
most trips in a year. 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 percent nationally.

Taking a slightly different perspective, Kempton and Tomić compare the relative power of the U.S. electric generation with the U.S. light-duty vehicle fleet in 2005. In Table 3 we provide an updated version of the author’s 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). In short, BEVs and PHEVs are not necessarily cost-effective for producing lots 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 their response time can be as rapid as tens of milliseconds.

Table 3. Utility electric generation compared with the light-duty vehicle fleet, for the United States in 2015.a

<table>
<thead>
<tr>
<th>Metric of comparison</th>
<th>Electric generation system</th>
<th>Current light-duty vehicle fleet (mechanical power)</th>
<th>Projected light-duty vehicle fleet, if BEVs 50% of light-duty vehicle stock? (electrical power)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of units (vehicles and power plants)</td>
<td>7453b</td>
<td>240,155,000i</td>
<td>120,180,000</td>
</tr>
<tr>
<td>Average unit power (kW)</td>
<td>142,769</td>
<td>171 kW m</td>
<td>10 kW m</td>
</tr>
<tr>
<td>Total system power capacity (GW)</td>
<td>1,064c</td>
<td>40,994 GW m</td>
<td>1,202</td>
</tr>
<tr>
<td>In-use duty cycle</td>
<td>42%d</td>
<td>4% k</td>
<td>4%</td>
</tr>
<tr>
<td>Response time (off to full power)</td>
<td>Minutes to hours</td>
<td>seconds</td>
<td>Tens of milliseconds to seconds</td>
</tr>
<tr>
<td>Design lifetime (h)</td>
<td>80,000 – 200,0000h</td>
<td>4,200 j</td>
<td>4,200+</td>
</tr>
<tr>
<td>Capital cost ($US/kW)</td>
<td>1000 - 7,000m $/kW</td>
<td>$90m $/kW m</td>
<td>50 - 150o $/kW</td>
</tr>
<tr>
<td>Cost of electric energy ($US/kWh)</td>
<td>.10h</td>
<td>n.a.</td>
<td>.19p</td>
</tr>
</tbody>
</table>

a Based on Table 1 in Kempton and Tomić 2005b (“… implementation…”), with numbers from original 2004 data updated here to reflect 2015 data.
c. EIA, Table 4.7.A, Summer total 2015 Capacity.
d. EIA, Total generation (Table 7.2.B, electricity net generation, divided by Total system power capacity * 8760 h/y.
e. Gas turbines about 10–15min, 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 4000h/year thus a design life of 80,000h. A large coal plant with a design lifetime of 30 years, operated at 75% capacity factor or approximately 8000 h/year would have a lifetime of about 200,000 h. From: Table 1, Kempton & Tomić 2005b.
h. EIA Electricity Data Browser, Annual, Average US Retail price for 2015. Peak power prices can be several times higher over some hours.
4.2 Financial: electric utility revenues

As implied in the section above, 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), or grid services back to electric utilities. While the specifics would differ according to local electricity markets, VGI vehicles could become more like “cash cows” (a product that generates a steady profit) that produce income from existing equipment and less like vehicles that merely consume energy. 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, while a PEV providing regulation could earn up to $US 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 $US 100-$300/year per participating vehicle in the study year. As an illustration, 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 of study—all of which can greatly impact estimates of financial benefits. In particular, modeling studies tend to estimate higher values when they account for more potential VGI benefits, such as avoiding capacity additions. 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 estimate of VGI value.
Table 4: Illustrative summary and comparison of VGI modeling approaches and estimates of net-present value

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>PEV adoption</td>
<td>Exogenous: 100% PEV market share</td>
<td>Exogenous: 0% to 15% PEV market share by scenario</td>
<td>Exogenous: 0% to 60% PEV market share by scenario</td>
<td>Exogenous: 0% to 30% PEV market share by scenario</td>
<td>Exogenous: 25% PEV market share</td>
<td>Exogenous: 1% to 15% PEV market share by scenario</td>
<td>Endogenous: PEV adoption is simulated</td>
</tr>
<tr>
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<td>Exogenous: PEVs charge at night, or utility minimizes costs with V1G charging or V2G</td>
<td>Exogenous: Utility uses V2G to minimize system costs</td>
<td>Exogenous: PEVs charge at night, or utility minimizes costs with V1G</td>
<td>Exogenous: PEV owners minimize charging cost in response to real-time pricing</td>
<td>Exogenous: PEV owners minimize charging cost in response to real-time pricing</td>
<td>Exogenous: PEV owners minimize charging cost in response to real-time pricing</td>
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<td>Optimized capacity additions</td>
<td>Optimized capacity additions with scenarios exploring impact of greater wind capacity</td>
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<td>Optimized capacity additions with scenarios exploring impact of greater wind capacity</td>
<td>Optimized</td>
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<tr>
<td>Hourly generation (i.e. utilization)</td>
<td>Optimized</td>
<td>Optimized</td>
<td>Optimized</td>
<td>Optimized</td>
<td>Optimized</td>
<td>Optimized</td>
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<tr>
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<tr>
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<td>Regional grids, eastern United States</td>
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<td>Connected regional grids, Alberta and British Columbia, Canada</td>
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<tr>
<td>VGI impact</td>
<td>Reduces excess wind generation by roughly one third</td>
<td>V2G avoids 20-30% of the GHG emissions resulting from PEV electricity demand</td>
<td>Savings with VGI have net-present value of $50-$450 per vehicle per year, higher where new capacity must be added</td>
<td>Savings of VGI are $75-$225 per vehicle per year, higher with more wind capacity</td>
<td>Reduces excess wind and solar generation by roughly two thirds</td>
<td>Savings of VGI are $70-$120 per vehicle per year, higher with more wind capacity</td>
<td>Savings of VGI are $50-$125 per vehicle per year, higher with more wind and solar capacity</td>
</tr>
</tbody>
</table>

Source: 76
Some studies suggest that some types of vehicle fleets could earn even more revenue than passenger vehicles, especially fleets with predictable driving patterns.\textsuperscript{77} For example, Noel and McCormack found that compared to diesel fueled school buses, in certain conditions VGI enabled electric school buses could save school districts about $6000 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.\textsuperscript{78} Similarly, De Losi Rios et al found, compared to diesel–fueled trucks, V2G enabled electric trucks could have 5–11\% lower life-time ownership cost.\textsuperscript{79}

In exploring the potential revenue benefits of V2G at the utility level, The Pacific Northwest National Laboratory 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)\textsuperscript{80}. They concluded that with 60 percent penetration in the light-duty vehicle market, PHEVs would 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 V2G cars 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 are likely bring profit to particular organization, providing incentive for that organization to manage the VGI potential of some subset of vehicles.\textsuperscript{81, 82, 83} 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 set up.\textsuperscript{84}

4.3 Socioenvironmental: mitigated emissions and integration of renewables

The socioenvironmental 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 greenhouse gas emissions from the transport sector substantially, though the majority of emissions savings have nothing to do with the fact that vehicles are VGI capable, only that they are electric. Much of this benefit comes from nature of PEVs. Using an extensive database on carbon dioxide 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, carbon dioxide emissions would be reduced an average of 42 percent. In
the United Kingdom, PEVs have the potential to reduce carbon dioxide (CO2) emissions by 62-65%
compared to IC vehicles by 2030. Further studies reiterate the same general conclusion: PHEVs and
BEVs can reduce greenhouse gases significantly even when operating in a wide variety of conditions.

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 percent and 98 percent, respectively, under a scenario of VGI penetration and
total NOx emissions would also be reduced by 31 percent. In tempering their findings, the authors
cautions that total particulate matter emissions would increase 18 percent and SOx emissions would
increase by 125 percent if the EVs 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 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 NOx emissions even during the ozone season, despite the
additional load for charging, and that by adding services such as spinning reserves and storage, SO2
and NOx emissions would be reduced even further.

Finally, a VGI system can further accrue environmental benefits by providing storage support
for intermittent renewable-energy generators. In other words, the batteries in the vehicles could store
electricity produced by wind turbines, for example, and provide the power back to the grid when
needed. The power produced from the turbines fluctuates greatly due to wind gusts, cloud cover,
thermal cycles, the movement of weather fronts, and seasonal changes. Given that they produce
most of their electricity at night, just when PEVs would need recharged, a VGI strategy could greatly
help level daily fluctuations in wind power. PEVs could offset the need for spinning reserves and
load management necessary to integrate these intermittent resources (and others, such as solar
photovoltaics) into the grid. 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. 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 grid, the Californian and
German electricity grids, and in Denmark.
4.4 Behavioral: Cost savings and environmental benefits

The two main benefits that VGI can offer to consumers clearly flow from two of the more general benefits we discuss above: cost savings and environmental benefits. Discrete-choice modeling research in the US finds that potential BEV drivers would require a high degree of annual compensation to enroll in some form of V2G program, ranging from $2000 to over $8000 per year.\textsuperscript{109} 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.\textsuperscript{110} Consumer segmentation identified four different segments, including a “cost-focused” segment representing 33% of the sample of over 1700 new vehicle buying households. Notably, the policy scenarios that offered a 20% savings on electrical bill 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.\textsuperscript{111} 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 the reduced environmental impact, 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 and Kurani explored the idea of pairing the sale of a PEV with consumer enrollment in a renewable electricity program, using a web-based survey of 1502 US new vehicle buyers (1064 conventional vehicle owners, 364 hybrid vehicle owners, and 74 PEV owners).\textsuperscript{112} Among the conventional (“Mainstream”) vehicle owners, offering a green electricity program to accompany a PEV purchase increased stated interest in PEVs by 23%. 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.\textsuperscript{113} 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 about 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 7 times more highly than the mainstream sample. 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, socioenvironmental, 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 upon additional electronic, communication, and control costs. Hein et al. 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, though early work at the University of Delaware suggests they are surmountable. The impact of EV 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. Green et al. 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. The only published quantitative answer comes from Honda—testing the challenging case of a continuously-running grid service over the warrantee life, they find that driving caused 8% battery degradation and continuous VGI added another 2%. 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 payment. Although Peterson et al. found only a mild effect between V2G services and battery wear, Bishop et al. concluded that V2G provision will require multiple, additional battery replacements over the lifetime of the vehicle. Marongiu et al
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 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 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. 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 as well as an inability to fully substitute for mobility and transport markets. 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. 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. 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” needed to make intelligent decisions about fuel economy.

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

Another class of challenges falls into the socioenvironmental category, and encompasses the negative externalities associated with VGI systems, especially those associated with the increased adoption of EVs. Although both PEVs and a VGI configuration has 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. 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. 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.

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, solar, natural gas, VGI cars, and electric heat, modelling system reliability in the Northeastern part of the United States for four years of operation. 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 a number of potential barriers to consumer 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, prevent a threat in the case of emergency, or in the case of PHEVs, increase the proportion of gasoline powered miles relative to electricity-powered miles. 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. For example, reducing
guaranteed minimum range from 175 miles to 125 miles was valued as equivalent to a loss of $500 in upfront value, while the 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 64km range PHEV by 10km, with one “charge-focused” segment (representing 33% of the total sample) that was willing to pay over $300 per year.147 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 semi-structured 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.”148

Indeed, concern with how VGI engagement may impact the electric-powered range of a PEV have provoked some to even coin the term “range anxiety” to express concerns over how far BEVs can go in between charges.149 150 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”.151 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.152 However, early critics of the “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.153 Further, 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 VGI program would be an “invasion of privacy”, while 39% indicated that a VGI program might “take control away from me in a way that I would not like.”154 Several of these households explained their concerns with trust in follow-up structured interviews, for example, “I don’t find the concept bad, but...[it ]could go wrong...there’s some kind of bureaucracy [that] gets in there, and you may find yourself at odds with it.”155 Such research has informed some demonstration V2G programs, for example one program run by Nuuve that provides simple defaults but always give the driver ability to schedule typical trips, plan for one specific long trip, or simply to request filling the battery right away, all from either a web browser or a mobile app.156
Third 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.\textsuperscript{157} 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.\textsuperscript{158} In contrast PEV owners or “Pioneers” have a much easier time grasping the concept of VGI.\textsuperscript{159}

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 semi-structured interviews with 22 Canadian PEV owners, only a few households brought up battery degradation without being prompted.\textsuperscript{160} 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”. Accordingly, some households stated they would need either a guarantee from the utility, monetary compensation, or an extended battery warranty to accept VGI. OEMs are apparently aware of this potential issue, since those few now offering VGI vehicles explicitly cover V2G with the warrantee (for example, Nissan Europe honors the full warrantee on Leaf and e-NV200 EVs as long as power is does not exceed 10 kW).\textsuperscript{161}

Concerns about battery degradation can become more elevated in some cases of fleets and commercial usage. Although the data is dated, taxis offer one example, as they tend to have far heavier duty cycles than privately owned passenger vehicles. Researchers in New York surveyed the managers of 68 taxi fleet companies in 2008, who employed more than 13,000 taxi drivers in New York City, about their preferences for PHEVs.\textsuperscript{162} 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 will remain limited.

While not directly specific to VGI, we note a final potential market barrier to the PEV market relates to the supply of the vehicles. Matthews et al. surveyed consumer experiences with several different “EV-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.\textsuperscript{163} In related research, Cahill et al. found that many California dealers and salespersons expressed antagonism towards PEVs, since 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.” 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.

6 Research Gaps and a Critical Research Agenda

The sociotechnical perspective not only offers a comprehensive lens by which to appreciate the promise 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 vehicle-grid integration (different types of V1G and V2G), and methods of VGI engagement (time-of-use 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 towards 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 largescale transition to VGI can be achieved, overcoming the long-history of hypes, disappointments and failed transitions to alternative fuels and low-carbon technologies.  

Future research could draw from Weber and Rohracher’s framework of 12 different failures that prevent transformative change, divided into three different categories that we summarize with VGI examples in Table 5. First are market failures, which include knowledge spillover effects and investor short-sightedness that together lead to under-investment 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 largescale transition to VGI. Research could focus on better understanding and assessing the effectiveness of efforts to overcome such barriers. For example, research could study 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.  

Third are transformative system failures such as a lack of shared vision among key stakeholder or “directionality failure”, where different 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.”
### Table 5: Overview of VGI failures in the context of transformative change

<table>
<thead>
<tr>
<th>Type of failure</th>
<th>Examples of potential barriers to VGI</th>
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<tbody>
<tr>
<td>Market failures</td>
<td>1. Information asymmetries: Technology uncertainty among private investors leads to underinvestment in VGI-related technologies</td>
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<td></td>
<td>2. Knowledge spillover: Public-good aspect of VGI innovation leads to underinvestment in R&amp;D</td>
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<td></td>
<td>3. Externalization of costs: If negative environmental externalities are not internalized (e.g. policy is absent), then VGI could exacerbate such environmental impacts.</td>
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<td></td>
<td>4. Over-exploitation of commons: Poor designed VGI systems could over-exploit public-good aspects of the grid</td>
</tr>
<tr>
<td>Structural system failures</td>
<td>5. Infrastructural failure: Lack of necessary VGI infrastructure, including grid capacity, chargers, meters</td>
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<td></td>
<td>6. Institutional failure: Absence of needed laws, regulations and standards required to manage a VGI transition</td>
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<tr>
<td></td>
<td>7. Interaction or network failure: Small, closely-tied groups develop and pursue VGI visions that “lack infusion of new ideas”</td>
</tr>
<tr>
<td></td>
<td>8. Capabilities failure: Lack of competencies and resources regarding VGI at firm and actor level</td>
</tr>
<tr>
<td>Transformational system failures</td>
<td>9. Directionality failure: Lack of shared vision regarding the goal and direction of VGI and the VGI transformation process</td>
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<tr>
<td></td>
<td>10. Demand articulation failure: Lack of space to explore and understand user (consumer) needs to enable uptake of VGI</td>
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<tr>
<td></td>
<td>11. Policy coordination failure: Lack of multi-level policy coordination to support VGI, e.g. lacking provisions in low-carbon vehicle, fuel, and electricity policy to incentivize low-carbon VGI systems</td>
</tr>
<tr>
<td></td>
<td>12. Reflexivity failure: Inability of system to adapt to change and learning regarding VGI technology and user and firm behaviour</td>
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Note: Adapted to VGI examples by authors, quotations from 170

A related gap and line of inquiry is explicit exploration of the policies needed to overcome these transformative barriers, including Weber and Rohracher’s 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.171 Many regions instead rely on a patchwork of sector specific climate policies, including 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. For example, 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 incent the innovations and efforts that would inevitably be part of a full transition to VGI. Text Box 2 describes another transformative failure in practice, that of integrated Alternating Current (AC) Chargers.

**Text Box 2: Transformative Failures in Practice—The case of AC Chargers**

As one example of a directionality failure, most automobile OEMs have installed relatively simple, low-power 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 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 in the Renault ZOE, the MiniE, the standard charger on the BMW i3, and by truck and bus manufacturers 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 about 350 € of parts to the car.\(^{172}\) To provide the same amount of power from an external charger now costs in the range from 5,000 to 20,000 €—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 take 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”\(^{173}\), 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 independently by at least three independent teams, each with a handful of engineers (1 to 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.

6.3 Appreciating the complexity of users

Third, 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 or PEVs that all participate in a VGI program, with PEVs charging either according to an assumed schedule (e.g. (Lund & Kempton, 2008)), to optimize grid operations (e.g. (Weis, Jaramillo, & Michalek, 2014)), or to minimize the charging cost for individual PEV owners (e.g. (Druitt & Früh, 2012)). One study explicitly addressed the question for mainstream buyers, but that study presented the VGI case as requiring the EV driver to stay plugged in 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, suggesting reward for more rather than a set minimum might lead to higher VGI participation. 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 minimize “total cost of operation”).

However, consumer perceptions and motivations are typically more sophisticated and varied than those of an optimizing agent. While there are many behavioral theories to draw from, 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. 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” conscious. 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 emissions, air pollution or oil reliance. They distinguish between two types of societal frames summarized in Table 4. 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).181 182 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.183 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 (e.g. cost savings).

Table 5. Functional-Symbolic and Private-Societal Dimensions of Driver Behavior

<table>
<thead>
<tr>
<th>Functional</th>
<th>Symbolic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Private</strong></td>
<td><strong>Symbolic</strong></td>
</tr>
<tr>
<td>What it does for you, e.g.</td>
<td>What it represents, e.g.</td>
</tr>
<tr>
<td>• save money</td>
<td>• Expression of self-identity</td>
</tr>
<tr>
<td>• reliable</td>
<td>• Convey personal status</td>
</tr>
<tr>
<td>• fun to drive (experiential)</td>
<td>• Attain group membership</td>
</tr>
<tr>
<td><strong>Societal</strong></td>
<td><strong>What it says to society, e.g.</strong></td>
</tr>
<tr>
<td>What it does for society, e.g.</td>
<td>• Inspire other consumers</td>
</tr>
<tr>
<td>• Reduce air pollution</td>
<td>• Send message to automakers, government, oil companies</td>
</tr>
<tr>
<td>• Reduce global warming</td>
<td></td>
</tr>
<tr>
<td>• Reduce oil use</td>
<td></td>
</tr>
</tbody>
</table>

Source: 184

Further, the few studies that focus on consumer aspects of VGI tend to rely on surveys techniques including stated choice experiments, as well as a few cases that utilize interviews or focus groups. In such studies, it is important to consider the nature of the participant sample, including the representativeness of the sample, the country of focus, and whether the target population is 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 population of new vehicle buying households including the potential “next” or “early mainstream” PEV buyers.185 Thus, it seems
wise for future research of potential large-scale VGI systems to include data collection from Mainstream car buyers.

6.4 Towards interdisciplinary, multi-method modeling approaches

A final gap and potential priority for future VGI research is to move towards interdisciplinary and multi-method efforts. In our socio-technical summary in this Review, few studies reveal insights that cross more than one or two of the four categories we identify: technical, financial, socioenvironmental 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 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 across insights could occur through multi-method approaches. For example, while 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.\textsuperscript{186} Even more novel is to develop studies that directly integrate empirical data from surveys and interviews (as noted in the previous subsection) with models of VGI participation that in turn simulate the technical, economic and environmental impacts of such systems. For example, the seventh study (far right column) in Table 3 includes consumer-informed and endogenous representations of PEV purchase behavior and VGI participation, in tandem with an optimization model to represent the electrical grid.\textsuperscript{187} Most comprehensive of all would be a study approach that also adds in a higher level, institutional component to represent the system-level transformative failures that acts as barriers to a VGI transition.

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 to the twin dilemmas of environmental pollution and sustainable transitions. The transition could empower vehicles to simultaneously
improve the efficiency (and profitability) of electricity grids, reduce greenhouse gas 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. A sociotechnical systems focus is recommended, both as a unit of analysis and analytical tool, also 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. It also offers a subtle but strong critique to much of the techno-economic work done so far, since this paradigm presumes that individuals will make the same rational decisions as the modeled optimizing agents. History teaches 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 alone. Changes in consumption choices may be required to best prepare society for its future energy-related challenges. Moreover, 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.

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 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.

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