Vehicle-to-grid power fundamentals: Calculating capacity and net revenue

Willett Kempton*, Jasna Tomič
University of Delaware, Newark, DE 19716, USA

Received 12 November 2004; received in revised form 8 December 2004; accepted 8 December 2004
Available online 11 April 2005

Abstract

As the light vehicle fleet moves to electric drive (hybrid, battery, and fuel cell vehicles), an opportunity opens for “vehicle-to-grid” (V2G) power. This article defines the three vehicle types that can produce V2G power, and the power markets they can sell into. V2G only makes sense if the vehicle and power market are matched. For example, V2G appears to be unsuitable for baseload power—the constant round-the-clock electricity supply—because baseload power can be provided more cheaply by large generators, as it is today. Rather, V2G’s greatest near-term promise is for quick-response, high-value electric services. These quick-response electric services are purchased to balance constant fluctuations in load and to adapt to unexpected equipment failures; they account for 5–10% of electric cost—$12 billion per year in the US. This article develops equations to calculate the capacity for grid power from three types of electric drive vehicles. These equations are applied to evaluate revenue and costs for these vehicles to supply electricity to three electric markets (peak power, spinning reserves, and regulation). The results suggest that the engineering rationale and economic motivation for V2G power are compelling. The societal advantages of developing V2G include an additional revenue stream for cleaner vehicles, increased stability and reliability of the electric grid, lower electric system costs, and eventually, inexpensive storage and backup for renewable electricity.

© 2005 Elsevier B.V. All rights reserved.

Keywords: Electric vehicle; Fuel cell; Plug-in hybrid; Vehicle-to-grid power; Ancillary services; V2G

1. Introduction

The electric power grid and light vehicle fleet are exceptionally complementary as systems for managing energy and power. We compare these two systems briefly to introduce this article, and in more depth (with calculations and references) in a companion article [1]. The power grid has essentially no storage (other than its 2.2% capacity in pumped storage [2]), so generation and transmission must be continuously managed to match fluctuating customer load. This is now accomplished primarily by turning large generators on and off, or ramping them up and down, some on a minute-by-minute basis. By contrast, the light vehicle fleet inherently must have storage, since a vehicle’s prime mover and fuel must be mobile. Vehicles are designed to have large and frequent power fluctuations, since that is in the nature of roadway driving. The high capital cost of large generators motivates high use (average 57% capacity factor). By contrast, personal vehicles are cheap per unit of power and are utilized only 4% of the time for transportation, making them potentially available the remaining 96% of time for a secondary function.

Our comparison of the electric system with the light vehicle fleet becomes of practical interest as society contemplates electric-drive vehicles (EDVs), that is, vehicles with electric-drive motor powered by batteries, a fuel cell, or a hybrid drivetrain. EDVs can generate or store electricity when parked, and with appropriate connections can feed power to the grid—we call this vehicle-to-grid power or V2G power. The relatively lower capital costs of vehicle power systems and the low incremental costs to adapt EDVs to produce grid power suggest economic competitiveness with centralized
power generation. On the other hand, compared with large generators, vehicles have low durability (about 1/50 of the design operating hours) and high cost per kWh of electric energy, suggesting that V2G power should be sold only to high-value, short-duration power markets. As we’ll describe shortly, these power markets include regulation, spinning reserves, and peak power.

We began the article with a description of the V2G concept. Section 3 describes the three vehicle types, followed in Section 4 by a description of four electricity markets and their suitability to purchase V2G power. Finally, general equations are developed for capacity, cost, and revenue of electricity from EDVs. A companion article, “vehicle-to-grid power implementation”[1] more comprehensively compares the vehicle fleet and electric grid, proposes strategies to reconcile the differing needs of driver and grid operator, suggests business models, and outlines the steps to V2G implementation.

2. The concept of V2G

The basic concept of vehicle-to-grid power is that EDVs provide power to the grid while parked. The EDV can be a battery-electric vehicle, fuel cell vehicle, or a plug-in hybrid. Battery EDVs can charge during low demand times and discharge when power is needed. Fuel cell EDVs generate power from liquid or gaseous fuel. Plug-in hybrid EDVs can function in either mode.

Each vehicle must have three required elements: (1) a connection to the grid for electrical energy flow, (2) control or logical connection necessary for communication with the grid operator, and (3) controls and metering on-board the vehicle. These elements vary somewhat with the business model and are described in more detail in the companion article [1]. Fig. 1 schematically illustrates connections between vehicles and the electric power grid. Electricity flows one way from generators through the grid to electricity users. Electricity flows back to the grid from EDVs, or with battery EDVs, the flow is two ways (shown in Fig. 1 as lines with two arrows). The control signal from the grid operator (labeled ISO, for Independent System Operator) could be a broadcast radio signal, or through a cell phone network, direct Internet connection, or power line carrier. In any case, the grid operator sends requests for power to a large number of vehicles. The signal may go directly to each individual vehicle, schematically in the upper right of Fig. 1, or to the office of a fleet operator, which in turn controls vehicles in a single parking lot, schematically shown in the lower right of Fig. 1, or through a third-party aggregator of dispersed individual vehicles’ power (not shown). (The grid operator also dispatches power from traditional central-station generators using a voice telephone call or a T1 line, not shown in Fig. 1.)

3. Three EDVs: battery, fuel cell, and hybrid

Three types of EDVs are relevant to the V2G concept: (1) battery, (2) fuel cell, and (3) hybrid. All are EDVs, meaning that they use an electric motor to provide all or part of the mechanical drive power. All but the smallest EDV electric motors are driven by power electronics with sinusoidal AC at varying frequencies, with the capability of being set to the grid’s 60 Hz. Thus, most of the power conditioning needed for grid power is already built-in and paid for as part of the transportation function. (Very small electric vehicles, such as a typical golf cart or neighborhood electric vehicle, typically use direct current motors and would require substantial additional power electronics to provide 60 Hz AC.)

3.1. Battery EDVs

Battery vehicles store energy electrochemically in the batteries, with lead-acid currently cheapest but with nickel metal-hydride (NiMH), lithium-ion, and lithium-metal-polymer batteries becoming more competitive due to longer cycle life, smaller size and lower weight. Operationally, they plug in to charge their batteries and unplug to drive. Battery vehicles must have grid connections for charging, so the
incremental costs and operational adjustments to add V2G are minimal.

3.2. Fuel cell EDVs

Fuel cell EDVs typically store energy in molecular hydrogen (H₂), which feeds into a fuel cell along with atmospheric oxygen, producing electricity with heat and water as by-products. Multiple options for on-board storage or production of hydrogen are under development, including pressurizing the H₂ gas, binding it to metals, and on-board production of H₂ from natural gas, methanol, gasoline or another fuel. Currently, distribution infrastructure, on-board storage of hydrogen, and conversion losses are all substantial problems that leave open the question as to whether fuel cell light vehicles will be practical and cost-effective [3,4].

Fuel cell EDVs used for V2G would produce electricity from the fuel cell, converted to 60 Hz AC by the on-board power electronics and supplied to the grid. Any cost of grid connection is outside the transportation function, so in this analysis, the cost and driver inconvenience of plugging in a fuel cell vehicle are attributed to V2G costs.

3.3. Hybrid EDVs

Contemporary hybrid vehicles use an internal combustion (IC) engine whose shaft drives a generator. A small battery buffers the generator and absorbs regenerative braking. The battery and generator power one or more electric motors that drive the wheels, possibly in conjunction with direct shaft power from the IC engine. More conceptually, a hybrid has one power system with large energy storage—for range—and a second with high power output and discharge-recharge capability—for acceleration and regenerative braking. For simplicity, we discuss here only the contemporary hybrids with internal combustion engine and battery, although the principles and equations we develop apply to any hybrid type.

The hybrids being mass-produced at the time this article is being written (the Toyota Prius, Honda Insight, and Civic-hybrid) have much larger mechanical than electric drive power (approximately 75–25%), small batteries (1–2 kWh) and no electrical connection to the grid. This combination makes today’s most-common hybrids impractical for V2G power. The coming “plug-in hybrid” makes two important additions: an enlarged battery and an electric plug to recharge [5], like the preproduction DaimlerChrysler Sprinter [6]. The larger battery (6 kWh or more) allows running in all-electric mode for at least 20 miles, a mode having advantages of lower fuel cost, home refueling convenience, and zero tailpipe emissions.

In relation to V2G, the plug-in hybrid has a grid connection for its transportation function and a large enough battery to provide V2G from the battery alone. In this article, our analysis of hybrids covers only the plug-in hybrid. The plug-in hybrid can provide V2G either as a battery vehicle (that is, not using the IC engine when doing V2G), or as a motor-generator (using fuel while parked to generate V2G electricity).

We next define the relevant power markets, and then develop the basic equations for V2G.

4. Power markets

Electricity is grouped in several different markets with correspondingly different control regimes. Here we discuss four of them—baseload power, peak power, spinning reserves, and regulation—which differ in control method, response time, duration of the power dispatch, contract terms, and price. We focus particularly on spinning reserves and regulation, which must deliver power within minutes or seconds of a request. All these electricity resources are controlled in real-time by either an integrated electric utility or an Independent System Operator—to refer to either of these parties here we use the simpler term “grid operator.” Our companion article discusses an additional near future electricity market, storage of renewable energy, which can be approximated as combinations of the existing markets.

The terminology and specifics of grid control differ across countries and even across jurisdictions within federalized countries. Although we draw on US standards, markets, and terminology [7,8], the same basic types of control and power response are needed in any large power grid.

4.1. Baseload power

Baseload power is provided round-the-clock. In the US this typically comes from large nuclear or coal-fired plants that have low costs per kWh. Baseload power is typically sold via long term contracts for steady production at a relatively low per kW price. V2G has been studied across multiple markets [9–13], showing that EDVs cannot provide baseload power at a competitive price. This is because baseload power hits the weaknesses of EDVs—limited energy storage, short device lifetimes, and high energy costs per kWh—while not exploiting their strengths—quick response time, low standby costs, and low capital cost per kW.

4.2. Peak power

Peak power is generated or purchased at times of day when high levels of power consumption are expected—for example, on hot summer afternoons. Peak power is typically generated by power plants that can be switched on for shorter periods, such as gas turbines. Since peak power is typically needed only a few hundred hours per year, it is economically sensible to draw on generators that are low in capital cost, even if each kWh generated is more expensive. Our earlier studies have shown that V2G peak power may be economic under some circumstances [9,11,14,15]. The required duration of peaking units can be 3–5 h, which for V2G is possible but difficult due to on-board storage limitations. Vehicles
could overcome this energy-storage limit if power was drawn sequentially from a series of vehicles, or if there were home refueling (say, with natural gas), options analyzed elsewhere [14] but not covered here.

4.3. Spinning reserves

Spinning reserves refer to additional generating capacity that can provide power quickly, say within 10 min, upon request from the grid operator. Generators providing spinning reserves run at low or partial speed and thus are already synchronized to the grid. Spinning reserves are the fastest response, and thus most valuable, type of operating reserves; operating reserves are “extra generation available to serve load in case there is an unplanned event such as loss of generation” [16].

Spinning reserves are paid for by the amount of time they are available and ready. For example, a 1 MW generator kept “spinning” and ready during a 24-h period would be sold as 1 MW-day, even though no energy was actually produced. If the spinning reserve is called, the generator is paid an additional amount for the energy that is actually delivered (e.g., based on the market-clearing price of electricity at that time). The capacity of power available for 1 h has the unit MW-h (meaning 1 MW of capacity is available for 1 h) and should not be confused with MWh, an energy unit that means 1 MW is flowing for 1 h.

These contract arrangements are favorable for EDVs, since they are paid as “spinning” for many hours, just for being plugged in, while they incur relatively short periods of generating power. Contracts for spinning reserves limit the number and duration of calls, with 20 calls per year and 1 h per call typical maxima [17]. As spinning reserves dispatch time lengths, from the typical call of 10 min to the longest contract requirement, 2 h, fueled vehicles gain advantage over battery vehicles because they generally have more energy storage capacity and/or can be refueled quickly for driving if occasionally depleted by V2G.

Spinning reserves, along with regulation (discussed next), are forms of electric power referred to as “ancillary services” or A/S. Ancillary services account for 5–10% of electricity cost, or about $12 billion per year in the U.S. [18,19], with 80% of that cost going to regulation [20].

4.4. Regulation

Regulation, also referred to as automatic generation control (AGC) or frequency control, is used to fine-tune the frequency and voltage of the grid by matching generation to load demand. Regulation must be under direct real-time control of the grid operator, with the generating unit capable of receiving signals from the grid operator’s computer and responding within a minute or less by increasing or decreasing the output of the generator. Depending on the electricity market and grid operator, regulation may overlap or be supplemented by slower adjustments, including “balancing service” (intrahour and hourly) and/or “load following.” Here, we analyze only regulation, but V2G may be appropriate for some of these other services.

Some markets split regulation into two elements: one for the ability to increase power generation from a baseline level, and the other to decrease from a baseline. These are commonly referred to as “regulation up” and “regulation down”, respectively. For example, if load exceeds generation, voltage and frequency drop, indicating that “regulation up” is needed. A generator can contract to provide either regulation up, or regulation down, or both over the same contract period, since the two will never be requested at the same time. Markets vary in allowed combinations of up and down, for example, PJM Interconnect requires contracts for an equal amount of regulation up and down together, whereas California Independent System Operator (CAISO) is more typical in allowing contracts for just one, or for asymmetrical amounts (e.g., 1 MW up and 2 MW down).

Regulation is controlled automatically, by a direct connection from the grid operator (thus the synonym “automatic generation control”). Compared to spinning reserves, it is called far more often (say 400 times per day), requires faster response (less than a minute), and is required to continue running for shorter durations (typically a few minutes at a time). The actual energy dispatched for regulation is some fraction of the total power available and contracted for. We shall show that this ratio is important to the economics of V2G, so we define the “dispatch to contract” ratio as

\[
R_{\text{d-c}} = \frac{E_{\text{disp}}}{P_{\text{contr}} t_{\text{contr}}} \tag{1}
\]

where \(R_{\text{d-c}}\) is the dispatch to contract ratio (dimensionless), \(E_{\text{disp}}\) the total energy dispatched over the contract period (MWh), \(P_{\text{contr}}\) the contracted capacity (MW), and \(t_{\text{contr}}\) is the duration of the contract (h). \(R_{\text{d-c}}\) is calculated separately for regulation up or down.

We have found that this \(R_{\text{d-c}}\) ratio is not tracked or recorded. We requested information on it from six US utilities and grid operators, none of whom recorded it nor knew its approximate value; most could not easily provide the quantities needed for us to calculate it [14]. We therefore resorted to calculating this ratio ourselves from a short period of intensively monitored data. Using data from CAISO of frequency regulation needed during the course of 1 day (unpublished data from Alec Brooks) and modeling the response of one EDV, we obtained \(R_{\text{d-c}}\) of 0.08. We conservatively use 0.10 in our analysis (“conservative” because higher \(R_{\text{d-c}}\) increases the cost of V2G).

5. Power capacity of V2G

How much V2G power can a vehicle provide? Three independent factors limit V2G power: (1) the current-carrying capacity of the wires and other circuitry connecting the
vehicle through the building to the grid, (2) the stored energy in the vehicle, divided by the time it is used, and (3) the rated maximum power of the vehicle’s power electronics. The lowest of these three limits is the maximum power capability of the V2G configuration. We develop here analysis for factors 1 and 2, since they are generally much lower than 3.

We shall first develop equations to calculate the limit on V2G by line capacity. Second, we develop equations to calculate the limit on V2G power by the vehicle’s stored energy, divided by the dispatch time. We then calculate several examples of limits, using two vehicles, across the markets of regulation services, spinning reserves, and peak power.

5.1. Power limited by line

Vehicle-internal circuits for full-function electric vehicles are typically upwards of 100 kW. For comparison, a US home maximum power capacity is typically 20-50 kW, with an average draw closer to 1 kW. To calculate the building-wiring maximum, one needs only the voltage and rated ampere capacity of the line:

\[ P_{\text{line}} = VA \]  

(2)

where \( P_{\text{line}} \) is power limit imposed by the line in watts (here usually expressed in kW), \( V \) the line voltage, and \( A \) is the maximum rated current in amperes. For example in the US, with home wiring at 240 V AC, and a typical 50 A circuit rating for a large-current appliance such as an electric range, with home wiring at 240 V AC, and a typical 50 A circuit maximum rated current in amperes. For example in the US, usually expressed in kW), \( P_{\text{line}} \)

maximum, one needs only the voltage and rated ampere capacity of the line:

\[ P_{\text{line}} = VA \]  

(2)

where \( P_{\text{line}} \) is power limit imposed by the line in watts (here usually expressed in kW), \( V \) the line voltage, and \( A \) is the maximum rated current in amperes. For example in the US, with home wiring at 240 V AC, and a typical 50 A circuit rating for a large-current appliance such as an electric range, the power at the appliance is 50 A \( \times \) 240 V so Eq (2) yields a line capacity of 12 kW maximum for this circuit. Based on typical US home circuits, some would be limited to 10 kW, others to 15 kW as the \( P_{\text{line}} \), limit. For a commercial building, or a residential building after a home electrical service upgrade (at additional capital cost), the limit could be 25 kW or higher. The assumptions behind these figures are discussed in detail in our companion article ([1]), Appendices A.1 and A.2.

On the vehicle side, most existing (pre-V2G) battery vehicle chargers use the National Electrical Code (NEC) “Level 2” standard of 6.6 kW. The first automotive power electronics unit designed for V2G and in production, by AC Propulsion, provides 80 A in either direction, thus, by Eq. (2), 19.2 kW at a residence (240 V) or 16.6 kW at a commercial building (208 V). This V2G unit also provides plug-in hybrids running V2G, ORA, or two charging levels, providing DC-watt-hour (Wh) energy storage. This V2G charger can be modified to add a large-capacity battery, or other power electronics.

5.2. Power limited by vehicle’s stored energy

The previous section analyzed V2G power as limited by the line capacity. The other limit on V2G power is the energy stored on-board divided by the time it is drawn. More specifically, this limit is the onboard energy storage less energy used and needed for planned travel, times the efficiency of converting stored energy to grid power, all divided by the duration of time the energy is dispatched. This is calculated in Eq. (3)

\[ P_{\text{vehicle}} = \frac{E_{\text{vehicle}} - d_{\text{rb}} d_{\text{disp}}}{\eta_{\text{veh}} t_{\text{disp}}} \]  

(3)

where \( P_{\text{vehicle}} \) is maximum power from V2G in kW, \( E_{\text{vehicle}} \) the stored energy available as DC kWh to the inverter, \( d_{\text{rb}} \) the distance driven in miles since the energy storage was full, \( d_{\text{disp}} \) the distance in miles of the range buffer required by the driver (explained below), \( \eta_{\text{veh}} \) the vehicle driving efficiency in miles/Wh, \( \eta_{\text{inv}} \) the electrical conversion efficiency of the DC to AC inverter (dimensionless), and \( t_{\text{disp}} \) is time the vehicle’s stored energy is dispatched in hours.

In a specific application of Eq. (3), \( d_{\text{rb}} \) would depend on the driving pattern, the vehicle type (e.g., battery EDVs may be recharged at work), and the driver’s strategies for being prepared to sell power. The value of \( d_{\text{disp}} \) we use in examples here derives from the average daily vehicle miles traveled per US driver of 32 miles [23]. We assume here that half the average daily vehicle miles would have been depleted when the vehicle is parked and power is requested (i.e. \( d_{\text{rb}} = 16 \) miles). The \( d_{\text{rb}} \) refers to the “range buffer,” the minimum remaining range required by the driver. It is not an engineering measure of the vehicle but is specified by the driver or fleet operator who will determine \( d_{\text{rb}} \) based on, for example, the return commute or the distance reserved for an unanticipated trip to a convenience store or hospital. Based on interviews with California drivers, Kurani et al. [24] found that 20 miles was sufficient for most drivers. We use 20 miles for \( d_{\text{rb}} \) for battery and fuel cell vehicles; plug-in hybrids running V2G from their batteries can drain the battery and use fuel if driving is needed before recharge, so we assume \( d_{\text{rb}} = 0 \) for plug-in hybrids.

The time dispatched (\( t_{\text{disp}} \)) will depend on the electricity market. For peak power, a reasonable value for \( t_{\text{disp}} \) is 4 h. For spinning reserves, although typical dispatches are 10 min, we calculate based on \( t_{\text{disp}} = 1 \) h here to insure that a 1-h contract requirement can be met. For regulation up and down, power in a battery vehicle can flow both ways; although regulation dispatch is typically only 1–4 min, we use \( t_{\text{disp}} \) of 20 min to allow for the possibility of a long or repeated regulation up sequence. ¹

The fuel cell vehicle, or hybrid in motor-generator mode, can provide only regulation up (power flows from vehicle to grid), not regulation down (power from grid to vehicle), so it has no analogy to the battery EDV’s recharge during regulation down. ² Thus, for example, a fuel cell vehicle parked

¹ Some ISOs require that power plants contracted for regulation also provide blocks of power, up to 30 min, via the regulation signal. V2G-supplied regulation (as well as some forms of power plant-supplied regulation) would be most effective if such blocks were not dispatched within regulation contracts, and we do not include such blocks in \( t_{\text{disp}} \) for regulation.

² In theory, fuel cells can be run in both directions, but no practical two-way cell can be built from current materials. A fuel cell vehicle parked at an electrolyzer could be configured for regulation down and regulation up, but this configuration is so inefficient in energy conversions compared to a
The vehicle efficiency ($\eta$) and peak power, whereas the battery and plug hybrid vehicles can provide more power for spinning reserves. Table 1, for all vehicles, we assume 

$$\eta_{disp} = \frac{\eta_d}{\eta_d \eta_{charger} \eta_{storage}}$$

where $\eta_d$ is efficiency of charger, and $\eta_{storage}$ is efficiency of storage. Therefore, to a 20 or 25 kW line connection.

6. Revenue versus cost of V2G

The economic value of V2G is the revenue minus the cost. Equations for each are derived in the next two sections, followed by examples.

6.1. Revenue equations

The formulas for calculating revenue depend on the market that the V2G power is sold into. For markets that pay only for energy, such as peak power and baseload power, revenue is simply the product of price and energy dispatched. This can also be expanded, since energy is $Pt$,

$$r = \rho_d \ E_{disp} = \rho_d \ P_{disp} \ t_{disp}$$

where $r$ is the total revenue in any national currency (we use $ as a shorthand for the appropriate currency), $\rho_d$ the market rate of electricity in $/kWh, $P_{disp}$ the power dispatched in kW (for peak power $P_{disp}$ is equal to $P$, the power available for V2G), and $t_{disp}$ is the total time the power is dispatched.
in hours. (Throughout, we shall use capital $P$ for power and lower-case $p$ for price.) On an annual basis, peak power revenue is computed by summing up the revenue for only those hours that the market rate ($p_{\text{m}}$) is higher than the cost of energy from V2G ($c_{\text{en}}$, discussed later).

For spinning reserves and regulation services the revenue derives from two sources: a "capacity payment" and an "energy payment." The capacity payment is for the maximum capacity contracted for the time duration (regardless of whether used or not). For V2G, capacity is paid only if vehicles are parked and available (e.g., plugged in, enough fuel or charge, and contract for this hour has been confirmed). The energy payment is for the actual kWh produced; this term is equivalent to Eq. (4). Eq. (5) calculates revenue from either spinning reserves or regulation services, with the first term being the capacity payment and the second term the energy payment.

$$ r = (p_{\text{cap}} P t_{\text{cap}}) + (p_{\text{el}} E_{\text{disp}}) \tag{5} $$

where $p_{\text{cap}}$ is the capacity price in $/kW-h$, $P$ is the contracted capacity available (the lower of $P_{\text{vehic}}$ and $P_{\text{bus}}$), $t_{\text{cap}}$ is the time in hours the EDV is plugged in and available, and $E_{\text{disp}}$ is the energy dispatched in kWh. (Note that the capacity price unit, $$/kW-h$, means $$/kW capacity available during 1 h—whether used or not—whereas energy price units are the more familiar $$/kWh.)

For spinning reserves, $E_{\text{disp}}$ can be calculated as the sum of dispatches,

$$ E_{\text{disp}} = \sum_{i=1}^{N_{\text{disp}}} P_{\text{disp}} t_{\text{disp}} \tag{6} $$

where $N_{\text{disp}}$ is the number of dispatches, $P_{\text{disp}}$ the power of each (presumably equal to the vehicle capacity $P_t$), and $t_{\text{disp}}$ is the duration of each dispatch in hours. A typical spinning reserves contract sets a maximum of 20 dispatches per year and a typical dispatch is 10 min long, so the total $E_{\text{disp}}$ will be rather small.

For regulation services, there can be 400 dispatches per day, varying in power ($P_{\text{disp}}$). In production, these would likely be metered as net energy over the metered time period, $E_{\text{disp}}$ in Eq. (5). For this article, to estimate revenue we approximate the sum of $P_{\text{disp}}$ by using the average dispatch to contract ratio ($R_{\text{cap}}$) defined by Eq. (1), and rearrange Eq. (6) as Eq. (7)

$$ E_{\text{disp}} = R_{\text{cap}} P t_{\text{cap}} \tag{7} $$

Thus, for forecasting regulation services revenue (in a forecast, energy is estimated, not metered), Eq. (7) is substituted into Eq. (5), becoming Eq. (8)

$$ r = p_{\text{cap}} P t_{\text{cap}} + p_{\text{el}} R_{\text{cap}} P t_{\text{cap}} \tag{8} $$

6.2. Cost equations

The cost of V2G is computed from purchased energy, wear, and capital cost. The energy and wear for V2G are those incurred above energy and wear for the primary function of the vehicle, transportation. Similarly, the capital cost is that of additional equipment needed for V2G but not for driving. Assuming an annual basis, the general formula for cost is

$$ c = c_{\text{en}} E_{\text{disp}} + c_{\text{aw}} \tag{9} $$

where $c$ is the total cost per year, $c_{\text{en}}$ the cost per energy unit produced (calculated below), $E_{\text{disp}}$ the electric energy dispatched in the year, and $c_{\text{aw}}$ the annualized capital cost (calculated below).

For spinning reserves, again $E_{\text{disp}}$ would be computed by Eq. (6) and used in Eq. (9) to obtain annual cost.

For regulation, substituting Eq. (7) for $E_{\text{disp}}$ into Eq. (9), the total annual cost to provide regulation is

$$ c = c_{\text{en}} R_{\text{cap}} P t_{\text{cap}} + c_{\text{aw}} \tag{10} $$

where $c_{\text{en}}$ is the per kWh cost to produce electricity (also used in Eq. (9)). The equation for $c_{\text{aw}}$ includes a purchased energy term and an equipment degradation term

$$ c_{\text{aw}} = \frac{C_{\text{aw}}}{\eta_{\text{aw}}} + c_{\text{aw}} \tag{11} $$

where $c_{\text{aw}}$ is the purchased energy cost, and $c_{\text{aw}}$ is the cost of equipment degradation (wear) due to the extra use of V2G, in $/kWh of delivered electricity. The purchased energy cost $C_{\text{aw}}$ is the cost of electricity, hydrogen, natural gas, or gasoline, expressed in the native fuel cost units (e.g., $$/kg H_2$), and $\eta_{\text{aw}}$ is the efficiency of the vehicle’s conversion of fuel to electricity (or conversion of electricity through storage back to electricity). The units of $\eta_{\text{aw}}$ are units of electricity per unit of purchased fuel. Thus Eq. (11)’s computed $c_{\text{aw}}$, the cost of delivering a unit of electricity, is expressed in $$/kWh regardless of the vehicle’s fuel.

Degradation cost, $c_{\text{aw}}$, is calculated as wear for V2G due to extra running time on a hybrid engine or fuel cell, or extra cycling of a battery. For a fuel cell vehicle or hybrid running in motor-generator mode, degradation cost is

$$ c_{\text{aw}} = \frac{c_{\text{en}}}{{L}_{E}} \tag{12} $$

where $c_{\text{en}}$ is the capital cost per kW of the engine or fuel cell, including replacement labor in $$/kW/h, and $L_{E}$ is the engine or fuel cell lifetime in hours. The degradation cost, $c_{\text{aw}}$, is thus expressed in $$/kWh. For a battery vehicle, $c_{\text{aw}}$ is

$$ c_{\text{aw}} = \frac{c_{\text{m}}}{{L}_{E}} \tag{13} $$

where $c_{\text{m}}$ is battery capital cost in $ (including replacement labor), and $L_{E}$ is battery lifetime throughput energy in kWh for the particular cycling regime (discussed below).

The cost of degradation is zero if the vehicle life is less than the engine, fuel cell, or battery life due to driving plus V2G degradation, or if the battery’s shelf life is reached before the degradation/wear life,

$$ c_{\text{aw}} = 0 \tag{14} $$
Battery lifetime is often expressed in cycles, measured at a specific depth-of-discharge. For Eq. (13), we express battery life in energy throughput, $L_{ET}$, defined as

$$L_{ET} = L_c \times \text{DoD}$$

(15)

where $L_c$ is lifetime in cycles, $L$ is the total energy storage of the battery, and DoD is the depth-of-discharge for which $L_c$ was determined.

Shallow cycling has less impact on battery lifetime than the more commonly reported deep cycling. For example, test data on a Saft lithium-ion battery show a 3000-cycle lifetime at 100% discharge, and a 1,000,000-cycle lifetime for cycling at 3% discharge [26]. Using Eq. (15), the 3% cycle achieves 10 times the lifetime kWh throughput. For lead-acid and NiMH batteries, Miller and Brost [27] present similar results; their Fig. 8 suggests that batteries at 3% DoD yield about 28 times the throughput as they do at 80% DoD.

Deep cycling approximates V2G battery use for peak power or spinning reserves at longer dispatches, whereas the 3% cycling is closer to that of regulation services. Here we base battery life parameters on 80% discharge test cycle for peak power or spinning reserves, and approximate lifetime energy throughput at three times that amount when V2G is used for regulation services. The three times approximation is conservative—the above data suggest a 10 times or greater increase in lifetime throughput at the low DoD cycling regimes.

To make financial decisions, calculations are typically made on a yearly basis and capital cost is annualized. One way to annualize a single capital cost is to multiply it by the capital recovery factor (CRF) as expanded in Eq. (16)

$$c_{ac} = c_t \times \text{CRF} = c_t \frac{d}{1 - (1 + d)^{-n}}$$

(16)

where $c_{ac}$ is the annualized capital cost in $/year, $c_t$ is the total capital cost in $, d$ is the discount rate, and $n$ is the number of years the device will last.

6.3. Example: battery EDV providing regulation services

For a sample calculation of revenue and cost, we use the same RA V4 EV discussed earlier, providing regulation for the 2003 CAISO market. Revenue is calculated with Eq. (8). This vehicle’s parameters for Eq. (8) are listed in Table 2 and described under “comments.” The last entry is the resulting computed revenue. The total annual revenue calculated by Eq. (8) then for the RA V4 is $4928, with $3942 from capacity payments and $986 from energy payments.

Next we calculate costs for the RA-V4 to provide regulation services, using the cost parameters in Table 3 and Eq. (10). As shown in Table 3, the annual cost for RA-V4-provided regulation is $2374.

The net profit (revenue in Table 2 minus cost in Table 3) is $4928 – 2374 or $2554 a year. If we assume a 10 kW

---

**Table 2**

Calculation of revenue from a RA V4 EV providing regulation

<table>
<thead>
<tr>
<th>Revenue parameters</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{cap}$ (kW)</td>
<td>15</td>
<td>Use $P_{cap}$ because $P_{cap} \times P_{vehicle}$ (Table 1)</td>
</tr>
<tr>
<td>$\rho_{cap}$ ($/kW-h)</td>
<td>0.04</td>
<td>CAISO 2003 market prices [28] $0.02/kW-h for regulation up capacity plus the same for regulation down</td>
</tr>
<tr>
<td>$p_R$ ($/kWh)</td>
<td>0.10</td>
<td>Retail electricity price$^a$</td>
</tr>
<tr>
<td>$t_{plug}$ (h/year)</td>
<td>6570</td>
<td>Assume vehicle plugged in 18 h daily, so $t_{plug} = 18 \times 365 = 6570$ day/year</td>
</tr>
<tr>
<td>$R_{d}$ ( )</td>
<td>0.10</td>
<td>See text with Eq. (1)</td>
</tr>
<tr>
<td>$c$ ($)</td>
<td>4928</td>
<td>Revenue, result by Eq. (8)</td>
</tr>
</tbody>
</table>

$^a$ Retail electric rates are used on the RA V4 for revenue and subsequently for cost, so the net effect is paying retail for round-trip electrical losses.

---

**Table 3**

Calculation of cost of RA V4 EV providing regulation

<table>
<thead>
<tr>
<th>Cost parameters</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_p$ ($/kWh)$</td>
<td>0.10</td>
<td>Assume purchase at retail electric cost</td>
</tr>
<tr>
<td>$\eta_{sys}$ (%)</td>
<td>73</td>
<td>Round-trip electrical efficiency, grid-battery-grid</td>
</tr>
<tr>
<td>$c_{replacement}$ ($)</td>
<td>980</td>
<td>350 ($/kWh)$^2 \times 27.4 $/kWh + 10 h replacement labor $\times 30 ($/h)</td>
</tr>
<tr>
<td>$c_f$ ($/kWh)$</td>
<td>0.075</td>
<td>By Eq. (13)</td>
</tr>
<tr>
<td>$c_d$ ($/kWh)$</td>
<td>0.21</td>
<td>Result by Eq. (11)</td>
</tr>
<tr>
<td>$c_{plug}$ (kWh)</td>
<td>131520</td>
<td>This NiMH battery achieves 2000 cycles under deep cycle testing (EPRI 2003). By Eq. (11), $L_{ET} = 43840$ kWh for shallow DoD, we assume $3 \times L_{ET}$ (see text)</td>
</tr>
<tr>
<td>$c_r$ ($)</td>
<td>1900</td>
<td>Result by Eq. (16), assuming $d = 10$% $\times 10$ years, thus CRF=0.16</td>
</tr>
<tr>
<td>$c_{plug}$ ($/8$year)</td>
<td>304</td>
<td>On-board incremental costs $800$ [29]; wiring upgrade $1500$</td>
</tr>
<tr>
<td>$c$ ($)</td>
<td>2374</td>
<td>Cost, result by Eq. (10), assuming as before $P = 15$ kW and $t_{plug} = 6570$ h</td>
</tr>
</tbody>
</table>

$^a$ Assuming annual production of 100,000 batteries per year, EPRI estimates $350/kWh$ [30].

$^b$ If the plug capacity in a residence is to be greater than 6.6 kW, we assume wiring costs of $650$ for 10 kW and $1500$ for 15 kW. We assume custom, single-home costs and attribute the additional wiring costs to V2G costs, even though there would be transportation benefits such as fast charging. Wiring upgrades to a series of plugs in a parking structure or fleet lot would be far less, as would installation in new residences.
Table 4
Revenue from fuel cell vehicle providing spinning reserves

<table>
<thead>
<tr>
<th>Revenue parameters</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (kW)</td>
<td>15</td>
<td>Assume $P = P_{\text{line}} = P_{\text{disp}}$</td>
</tr>
<tr>
<td>$p_{\text{cap}}$ (S/kWh)</td>
<td>0.007</td>
<td>CAISO spinning reserves market price average for 2003 [28]</td>
</tr>
<tr>
<td>$p_{\text{el}}$ (S/kWh)</td>
<td>0.030</td>
<td>Assumed average spot energy price</td>
</tr>
<tr>
<td>$t_{\text{plug}}$ (h/year)</td>
<td>6570</td>
<td>Plugged in daily, 18 (h/day) $\times$ 365 (day/year)</td>
</tr>
<tr>
<td>$E_{\text{disp}}$ (kWh)</td>
<td>300</td>
<td>Assume 20 calls a year, each 15 kW for 1 h, per Eq. (6)</td>
</tr>
<tr>
<td>$r$ ($)</td>
<td>699</td>
<td>Revenue, result by Eq. (5)</td>
</tr>
</tbody>
</table>

Table 5
Cost of fuel cell vehicle providing spinning reserves

<table>
<thead>
<tr>
<th>Cost parameters</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\text{he}}$ (S/kg H$_2$)</td>
<td>5.6</td>
<td>High of projected hydrogen cost range [31]</td>
</tr>
<tr>
<td>$c_{\text{le}}$ (S/kg H$_2$)</td>
<td>1.7</td>
<td>Low of projected hydrogen cost range [31]</td>
</tr>
<tr>
<td>$\eta_{\text{conv}}$ (kWh/kg H$_2$)</td>
<td>13.57</td>
<td>For fuel cell, $\eta_{\text{conv}} = \eta_{\text{FC}} \eta_{\text{inv}}$; $\eta_{\text{FC}} = 14.75$ kWh/kg H$<em>2$; $\eta</em>{\text{inv}} = 0.92$</td>
</tr>
<tr>
<td>$c_{\text{d}}$ (S/kWh)</td>
<td>0.0025</td>
<td>Mid-range of degradation estimates: 3% over 10000 h, thus $L_h = 30000$ h; capital cost $c_{\text{d}} = 75$ S/kW (both per [32]); Eq. (12)</td>
</tr>
<tr>
<td>$c_{\text{en}}$ (S/kWh)</td>
<td>0.42</td>
<td>Per Eq. (11), high H$_2$ cost</td>
</tr>
<tr>
<td>$c_{\text{en}}$ (S/kWh)</td>
<td>0.13</td>
<td>Per Eq. (11), low H$_2$ cost</td>
</tr>
<tr>
<td>$c_{\text{ac}}$ ($)</td>
<td>399</td>
<td>Capital cost = $2450$ (see text); $d = 10%$; $n = 10$ years; CRF = 0.16; Eq. (16)</td>
</tr>
<tr>
<td>$c_{\text{ac}}$ ($)</td>
<td>399</td>
<td>Amortized as shown by Eq. (12) this gives an annual value of $c_{\text{ac}} = 399$. The total annual cost based on Eq. (5) and the values in Table 5, using the high estimate for hydrogen, is $525$. Thus, given the above assumptions, the net annual revenue is $174$. At low H$_2$ costs, the total annual cost is $438$ and the net is $262$. These figures illustrate that this result is not very sensitive to projected hydrogen prices, nor to energy payments (S/kWh), because spinning reserves involve very little energy transfer. However, the result is very sensitive to the capacity price for spinning reserves. For example, the ERCOT market is one of the higher US prices for spinning reserves—at 2003 ERCOT price of $23/MW-h$ [33] and again assuming the high end range of H$_2$ prices, the gross revenue is $2276$ and the net annual revenue is $1751$. More generally, fuel cell spinning reserves is economically viable only with a combination of good market prices and moderate capital costs; it is not sensitive to hydrogen costs.</td>
</tr>
<tr>
<td>$c_{\text{ac}}$ ($)</td>
<td>525</td>
<td>Cost, result by Eq. (9)</td>
</tr>
<tr>
<td>$c_{\text{ac}}$ ($)</td>
<td>438</td>
<td>Cost, result by Eq. (9)</td>
</tr>
</tbody>
</table>

6.4. Example: fuel cell EDV providing spinning reserves

The second net revenue example is the fuel cell vehicle selling spinning reserves. We use the fuel cell vehicle in these examples because, as suggested in Table 1 and our earlier work [14,29], the fuel cell vehicle is better matched to spinning reserves and peak power, the battery vehicle better matched to regulation. Values of the parameters in Eq. (5) are listed in Table 4 for this particular example. As shown in Table 4, the revenue for fuel cell vehicles selling spinning reserves is $699.

To calculate the annual costs for providing spinning reserves for the FC vehicles we use the values shown in Table 5, with Eqs. (9) and (11).

The capital costs are higher in this case because we assume that the transportation function of our example fuel cell vehicle would not require grid connection, thus the plug, wiring, and on-board connections must be charged entirely to the capital cost of V2G. We assume capital costs of $2450$.\(^3\)

\(^3\) Incremental capital costs of V2G for a fuel cell vehicle include on-board power electronics to synchronize the AC motor drive to 60 Hz and provide protection (445 S), and wires and plug for grid connection (200 S). On the building side, a 70 A, 240 V (16.8 kW) connection with ground fault interrupt but not NEC 625 compliant (only flow to grid, not charging, is contemplated) could range $50–5000$ at a residence, probably closer to $800$ in a fleet garage. Here we assume $1800$ on the building side, plus $450$ on-board, amortized as shown by Eq. (12) this gives an annual value of $c_{\text{ac}} = 399$. The total annual cost based on Eq. (5) and the values in Table 5, using the high estimate for hydrogen, is $525$. Thus, given the above assumptions, the net annual revenue is $174$. At low H$_2$ costs, the total annual cost is $438$ and the net is $262$. These figures illustrate that this result is not very sensitive to projected hydrogen prices, nor to energy payments (S/kWh), because spinning reserves involve very little energy transfer. However, the result is very sensitive to the capacity price for spinning reserves. For example, the ERCOT market is one of the higher US prices for spinning reserves—at 2003 ERCOT price of $23/MW-h$ [33] and again assuming the high end range of H$_2$ prices, the gross revenue is $2276$ and the net annual revenue is $1751$. More generally, fuel cell spinning reserves is economically viable only with a combination of good market prices and moderate capital costs; it is not sensitive to hydrogen costs.

6.5. Example: fuel cell EDV providing peak power

In Table 5, the values of the parameter $c_{\text{en}}$ range from $0.13$ to 0.42/kWh, depending on the assumed price of hydrogen. Since bulk power production is below $3.05/kWh, under our assumptions the fuel cell vehicle cannot compete with bulk power production from centralised plants. However, since peak power can be much more expensive per kWh, selling peak power may be economically viable despite its lack of a capacity payment.
The term “peak power” does not refer to a specific power market. Rather, it is used to refer to the highest cost hours of the year, when most or all generators are on-line and additional power is costly. A full analysis of the value of peak power requires stepping through hourly market values, assuming sales of V2G whenever the market value is above the cost of V2G and the vehicle is available, and summing the annual revenue (see [14]). To provide a simpler calculation here as an example, we use an industry rule of thumb from central California [14], that there are 200 h in an average year when additional generation costs $0.50/kWh. Based on this and the data in Table 5, we give in Table 6 parameters for calculating the revenue and cost of a fuel cell vehicle providing peak power. Thus the net revenue, based on Table 6, is $1500−1210, or $200, a positive annual net, but perhaps too small to justify transaction costs. This calculation is given only as an illustration. This result is highly dependent upon the cost of hydrogen (a mid-range projection was used here), the actual market prices for a representative year rather than the rule of thumb used here, and the match of peak time to vehicle availability. More complete analyses of V2G for peak power have been performed by Nagata and Kubo [15] and Lipman et al. [32].

7. Conclusions

We conducted technical analysis to understand the capacity of vehicles to provide power with minimal compromise of their primary function, transportation. We also investigated four major electricity markets, to find the best match of vehicle types to electric markets. To investigate these quantitatively, we developed equations to describe the available power and duration, and the costs and market value of these forms of power. The result we offer is a quantitative understanding of how electric drive vehicles can become part of the electrical grid, and methods for estimating the expected revenue and costs. Our conclusions suggest that vehicles probably will not generate bulk power, both because of their fundamental engineering characteristics and because our calculated per kWh cost of energy from vehicles is higher than bulk electricity from centralized generators. V2G most strongly competes for electricity when there is a capacity payment to be on line and available, with an added energy payment when power is actually dispatched. This is the case for the ancillary service markets of spinning reserves and regulation. For these markets, even if V2G power loses money on each kWh sold, it can more than make up for that with the capacity payment. V2G may be able to compete when paid only for energy, but only when electricity prices are unusually high, as in some peak power markets.

Existing electricity markets have been the focus of this article, because their prices are known and they offer a multi-billion dollar annual revenue streams to help move V2G innovations forward. In the process, V2G would improve the reliability and reduce the costs of the electric system. As described in our companion article [1], as V2G begins to saturate these high value markets, it will be positioned to play a more fundamental role—storage for the emerging 21st century electric system based primarily on intermittent renewable energy sources.

Acknowledgments

The development of these ideas and formulae has been facilitated by grants and contracts from the California Air Resources Board, the Los Angeles Department of Water and Power, Conectiv Power Delivery, and the Steven and Michele Kirsch Foundation. We are grateful for development and refinement of ideas in discussions and collaboration with Steve Letendre, Alex Brooks, Tom Gage, Tim Lipman, Dean Taylor and many others. We also appreciate discussions with many individuals in a number of electric utilities and ISOs, including Austin Energy, CAISO, Conectiv Power Delivery, NYISO, NYPA, PJM, Southern California Edison, Pacific Gas and Electric, and Sacramento Municipal Utility District. This article has been improved by comments from James Corbett, Dave Denkenberger, Karen E. Thomas-Alyea, and Robert Socolow.

Appendix A. Nomenclature and worksheet

This appendix lists the symbols, names, and units from the equations of this article. Table A.1 lists the primary data needed as inputs and Table A.2 names the resulting computed values. In Table A.1, the “vehicle/market” column indicates parameters needed for only a certain vehicle type or power market; if this column is blank, the same parameter applies to all vehicles or power markets. The empty “value” column allows a copy of this page to be used as a worksheet for parameters needed to make calculations for new vehicles or markets. Miles, gallons, and $ values can be replaced with appropriate national units, as long as all instances are substituted.

Table A.2 gives the values calculated by the equations in this article, along with the equations used to calculate them.
### Table A.1

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Vehicle/market</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line connection parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rated maximum circuit</td>
<td>$A$</td>
<td></td>
<td>Ampères</td>
<td></td>
</tr>
<tr>
<td>Line voltage</td>
<td>$V$</td>
<td></td>
<td>Volts</td>
<td></td>
</tr>
<tr>
<td><strong>Vehicle parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stored energy (available to inverter)</td>
<td>$E_s$</td>
<td></td>
<td>kWh</td>
<td></td>
</tr>
<tr>
<td>Vehicle efficiency</td>
<td>$\eta_{veh}$</td>
<td></td>
<td>Million/kWh</td>
<td></td>
</tr>
<tr>
<td>Efficiency of line AC to battery charge</td>
<td>$\eta_{charge}$</td>
<td></td>
<td>Dimensionless</td>
<td></td>
</tr>
<tr>
<td>Efficiency of inverter from DC to line AC</td>
<td>$\eta_{inv}$</td>
<td></td>
<td>Dimensionless</td>
<td></td>
</tr>
<tr>
<td>Efficiency of converting fuel to electricity</td>
<td>$\eta_{fcell}$</td>
<td></td>
<td>kW/kg H$_2$</td>
<td></td>
</tr>
<tr>
<td>Line AC voltage</td>
<td>$V$</td>
<td></td>
<td>Volts</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>$L_b$</td>
<td></td>
<td>h</td>
<td></td>
</tr>
<tr>
<td><strong>Vehicle operational parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time plugged-in</td>
<td>$t_{plug}$</td>
<td></td>
<td>h</td>
<td></td>
</tr>
<tr>
<td>Recharge once plugged in</td>
<td>$E_{recharge}$</td>
<td></td>
<td>kWh</td>
<td></td>
</tr>
<tr>
<td>Range buffer</td>
<td>$d_L$</td>
<td></td>
<td>Miles</td>
<td></td>
</tr>
<tr>
<td><strong>Market parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dispatch to contract ratio</td>
<td>$R_{d-c}$</td>
<td></td>
<td>Dimensionless</td>
<td></td>
</tr>
<tr>
<td>Time for one dispatch$^*$</td>
<td>$t_{disp}$</td>
<td></td>
<td>h</td>
<td></td>
</tr>
<tr>
<td>Price to sell V2G energy</td>
<td>$p_{el}$</td>
<td></td>
<td>$/kWh$</td>
<td></td>
</tr>
<tr>
<td>Capacity price</td>
<td>$P_{cap}$</td>
<td></td>
<td>SAW-h</td>
<td></td>
</tr>
<tr>
<td>Cost for EDV to buy energy</td>
<td>$c_{pe}$</td>
<td></td>
<td>$$/kWh, $$/kg H_2, $$/gal</td>
<td></td>
</tr>
</tbody>
</table>

$^*$ Maximum dispatch time for computing $P_{disp}$, average for computing $E_{disp}$.

### Table A.2

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Units</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispatch to contract ratio</td>
<td>$R_{d-c}$</td>
<td>Dimensionless</td>
<td>(1)</td>
</tr>
<tr>
<td>Power limit of line connection</td>
<td>$P_{line}$</td>
<td>W (or kW)</td>
<td>(2)</td>
</tr>
<tr>
<td>Power limit of vehicle’s stored energy</td>
<td>$P_{storage}$</td>
<td>kW</td>
<td>(3)</td>
</tr>
<tr>
<td>Total revenue</td>
<td>$S$</td>
<td>$/$</td>
<td>(4), (5), (8)</td>
</tr>
<tr>
<td>Discharged energy</td>
<td>$E_{disp}$</td>
<td>kWh</td>
<td>(6), (7)</td>
</tr>
<tr>
<td>Total cost per year</td>
<td>$c$</td>
<td>$$/year</td>
<td>(9), (10)</td>
</tr>
<tr>
<td>Cost per energy unit produced</td>
<td>$c_{o}$</td>
<td>$$/kWh$</td>
<td>(11)</td>
</tr>
<tr>
<td>Degradation cost</td>
<td>$c_d$</td>
<td>$$/kWh$</td>
<td>(12)-(14)</td>
</tr>
<tr>
<td>Battery lifetime, in throughput</td>
<td>$L_{bat}$</td>
<td>kWh</td>
<td>(15)</td>
</tr>
<tr>
<td>Annualized capital cost</td>
<td>$c_{ac}$</td>
<td>$$/year</td>
<td>(16)</td>
</tr>
</tbody>
</table>

References


