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Vehicle to Grid: An Economic and Technological Key to California's Renewable Future

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In partial fulfillment of a Bachelor of Arts Degree in Environmental Analysis,
2015-16 academic year, Pomona College, Claremont, California

Readers:
Bowman Cutter
John Jurewitz

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Introduction

Energy has been, and always will be, one of the most basic needs for promoting the well-being of humanity and economic growth. The late 19th century development of oil helped create an easily transportable and storable energy-dense commodity. In concert with the invention of the internal combustion engine, the development of oil supported economic growth and fundamentally restructured how energy was produced and consumed in the world. This time period saw the creation of two massive but separate energy conversion systems – the electric grid and the light vehicle transportation system. The development of the electric grid allowed energy stored in fossil fuels to be converted to electrical current, and subsequently transmitted through a vast network for easy consumer access to power. The second massive energy conversion system was simultaneously created as millions of passenger vehicles flooded the road, turning petrochemical energy to kinetic movement, allowing for travel and leading to creation of a huge national network of roads.

Why is it relevant to consider these two disparate energy systems simultaneously? As the 21st century faces the imminent threat of global warming and the eventual depletion of fossil fuels, the world must change the most common sources of energy away from combustible natural resources – the electric grid must shift towards renewable energy, and the transportation sector must move to adopt more electric vehicles (EVs). This paper explores the potential synergistic interaction of these two systems as we attempt to navigate this energy transition. The focus will be on California, a state with one of the most aggressive renewable transition policies, and how the connection of vehicles and the electric grid might simultaneously solve some of the state's largest grid operational challenges and environmental priorities.

The groundbreaking technology that is poised to lead a convergence of these two large power systems is called Vehicle-to-Grid or V2G. The potential V2G benefits

discussed in this paper are two fold. First, by connecting vehicle batteries with the electric grid and allowing power to flow both ways, the battery's ability to store and quickly release electricity can be used to stabilize some of the operational difficulties created by greater penetration of renewable generation. The second potential benefit of V2G is that this technology could bring a new stream of revenue for electric vehicle owners, creating important economic incentives to purchase an EV and further decreasing fossil fuel usage. Using California's unique renewable energy transition scenario, and projected data of electric grid features, this paper examines whether V2G could achieve this second benefit. As one of the first papers focusing specifically on V2G in California, this analysis will try to answer whether this new technology could bring these two-fold benefits to California and help the state in its transition towards a more renewable future.

The first section of the paper presents the history of V2G and explains the basic relationship between energy storage and the electric grid. The next section discusses how California's transition to a high renewable portfolio standard affects the grid. This section details two of the largest challenges the grid is projected to face – increased frequency regulation and renewable overgeneration – and then explains how V2G could potentially help alleviate some of the issues. The third section of the paper covers the business and economic framework that will be employed for calculating profits from V2G. This section also includes the equations for all of the calculations, as well as the data and assumptions that go behind the calculations. Next, the paper covers different potential business scenarios for V2G, and finally presents the study results for these scenarios. Lastly, using the results, the paper quantifies the different benefits V2G could have for California, and discusses other non-monetary benefits and challenges.

V2G: Background and Fundamentals

V2G History

The development of the EV in the early 21st century has revealed the critical significance of integrating the electric grid and the transportation sector. Rather than using fossil fuels to power its engine, the EV relies directly on electricity supplied from the grid. The extent of the interaction between a traditional EV and the electric grid is limited, however, power can flow from the grid to the vehicle, but electricity flow in the opposite direction is impossible. V2G takes this interaction one step further by allowing power to flow back and forth, or bi-directionally, from a vehicle battery to the grid while the vehicle is parked.

As EVs first began to penetrate the consumer market, V2G was introduced as a concept that could bring profit to the vehicle owner. As these first proponents of V2G argued, the vast majority of the world's population underutilizes vehicles and their batteries. Vehicles on average are used for transportation for less than 10% of each day – V2G technology introduces the concept of making this 90% of idle time productive (Turton, 2008). The technology first appeared in both energy engineering and economic journals at the beginning of the 2000s, pioneered mainly through the University of Delaware's Willett Kempton. Kempton released two papers in 2005 that explored the potential benefit of V2G for electricity consumers.

Kempton's first few studies on V2G portrayed the technology in the simplest sense: one vehicle, parked at a home, and charging/discharging through a local grid connection. These initial studies presented different possibilities of how V2G could be a useful service for any individual consumer of electricity. These studies found that the most beneficial and pragmatic use of V2G was through energy arbitrage, meaning the consumer purchases energy at a low cost point and then sells it back onto the grid when the cost is higher, creating revenues from the difference in prices (Kempton, Tomić

2005a).

For approximately the next four years, V2G studies focused mainly on profits that could be derived from buying electricity at low costs and selling at high prices. Kempton's second research paper in 2004, which used national electricity price data and put equations behind the costs and benefits of energy arbitrage, found that the system could bring profits to V2G users of approximately $100 per year (Kempton, Tomić 2005b). The model was simple: revenues accrued directly from the differences in electricity prices, and the only costs were those through battery degradation from increased charging/discharging. Kempton noted that many of the assumptions were unrealistic, such as perfect information about energy prices and zero transaction costs, but nonetheless concluded that energy arbitrage could be profitable. Similar studies in that time frame found profits ranging between $100-$250 annually, depending on the location and structure of the energy markets (Walawalkar et al., 2006) (Tomić & Kempton, 2007).

Kempton, along with other V2G studies in the early 2000s, kept the focus mainly on profit from energy arbitrage. Recently, however, the conversation has shifted. Rather than V2G being a technology used solely for personal gain (through energy arbitrage), scientists have begun to research whether vehicle batteries could also benefit the grid at large (Tomić & Kempton, 2007). Vehicle battery technology began to improve, resulting in more capacity for meaningful energy flow to and from the vehicle (Tomić & Kempton, 2007). In addition, the idea of the "smart-grid" began circulating, where multiple cars could communicate with one another and the grid, optimizing charging and discharging patterns (Petit & Perez, 2013). This concept was, and still remains revolutionary, for the future of transportation and a greener planet. In order to understand fully the potential for vehicle batteries benefitting the electric grid, one must first understand the basics of how the grid operates.

The Electric Grid

The electric grid is a system designed and constructed to stay in constant equilibrium.

The grid was built to be a vast network of transportation systems directly from multiple suppliers to multiple demanders. The amount of electricity being produced must instantaneously match the amount being used by consumers — at least within very tight tolerances. Otherwise, safety equipment on the grid will automatically interrupt the power flows to avoid damage to expensive equipment (NERC, 2013).

Electricity demand is difficult to predict and is constantly fluctuating. The California grid is managed by an Independent System Operator (ISO) known as CAISO. CAISO was established by the FERC like many other system operators, and is in charge of maintaining the electrical power system by coordinating, controlling and monitoring its operations (CAISO, 2015). The grid operator must take actions to maintain equilibrium so that supply does not exceed demand. Energy storage, such as the battery in an EV, is well suited for this job. When supply rises above demand, the battery can store the excess electricity so that equilibrium is maintained. Batteries that can transmit energy bi-directionally (*i.e.,* those that can also supply energy back to the grid) bring another benefit. When demand on the grid rises above supply, these batteries can send electricity back to the grid, increasing supply and bringing the grid back to equilibrium. Figure 1 shows a very simplified version of the demand and supply movement on the grid and the points at which batteries can benefit the grid.

Figure 1: V2G charge and discharge to balance supply and demand

If energy storage has the potential to provide important benefits to grid operation, a critical question is: why isn't energy storage already a significant part of electricity

operations? An approach that looks at the economic and institutional reasons yields important insight.

Energy Storage

The economic justification for new energy storage facilities is generally based on a direct comparison of the potential benefits of energy storage to an alternative option (choosing the lower net-cost option). Those traditional options historically have been oil and gas-powered plants that can quickly alter their electrical output to balance supply. Prices of oil and gas have kept these options economically favorable, as low-cost inputs keep the operating costs down (Denholm, 2010). Storage technologies, on the other hand, have historically not been worth considering economically due to their very high cost. Pumped hydro technology, where energy is stored in the form of gravitational potential energy, has been the only storage technology even remotely economically competitive. Yet, even in the 1980s during a period of oil price spikes, pumped hydro storage technology was installed only in insignificant quantities around the U.S (Ela et al., 2013). In addition, economic analysis on the benefits of energy storage has largely ignored any additional operational benefits energy storage can provide to the grid, mainly because understanding these values requires fairly sophisticated modeling and simulation methods (Denholm, 2010).

The favoring of traditional oil and gas solutions has led to the present situation where standard business models for electric utilities to invest in storage have not emerged (Ela et al., 2007). Perhaps one of the largest reasons for the continued lack of energy storage investment, despite the advances in battery technology, has to do with the time value of money. Research has shown that investors, such as utilities or independent power producers, tend to favor lower capital cost investments with faster construction times even if they have higher operating costs, because this reduces the perceived economic risk (Denholm, 2010). This means that combustion turbines have historically been the infrastructure of choice. This phenomenon of risk bias is present in other business sectors, as well. For example, Flyvbjerg (2013) found that many transportation infrastructure

projects (such as roads or rail) that require large investments have been delayed due to overestimated risk. Flyvbjerg's analysis shows that 84 percent of rail and road passenger preliminary forecasts in the early 21st century overestimated costs by more than ±20 percent. The unifying theme in these examples is the exaggerated perception of project risk, resulting either from an irrational fear of large up-front capital investment, or uncertainty in belief that expected project cash flows will in fact be achieved.

V2G technology is potentially most beneficial because it doesn't require large investments by utilities or grid operators for the storage. V2G participants invest in their vehicles' energy storage capacity to reduce the energy costs associated with personal transportation, but they achieve a "free rider" benefit in that the energy storage capacity of their vehicles can be used to generate profits because of the storage capacity they provide to the grid. The initial investment costs of V2G are therefore fundamentally different than those for batteries that are only used for energy storage.

Renewable Energy: An Added Stress to the Grid

Renewable's Unique Aspects

Energy storage is not only becoming more advanced and economically feasible through technologies like V2G, but is also becoming increasingly important with the introduction of large amounts of renewable energy to the grid. Renewable resources are inherently different from traditional thermal generation: they are subject to weather-dependent intermittent swings in production. Unlike traditional thermal generators that can produce electricity at specific amounts and times to match demand, solar and wind power produce energy whenever the sun is shining or whenever the wind is blowing. Instead of electricity *demand* being the difficult factor to predict on the grid, renewables create variability in generation, meaning that *supply* is also inconsistent. This creates tremendous challenges for the reliable operation of the electrical grid, and renders energy

storage even more essential in maintaining supply/demand equilibrium on an instantaneous and continual basis.

Transitioning from traditional thermal power generation to renewable energy has already proven to have major implications for the grid equilibrium. The National Renewable Energy Laboratory (NREL) found in a study of the Western U.S. grid that the added unreliability from renewable generation adds costs of between $0.47/MWh and $1.28/MWh from thermal generators having to cycle up and down more often to fill in electricity gaps (Bird, Milligan, & Lew, 2013). While some steps can be taken that will limit these added costs and operations difficulties to the grid (these steps will be discussed later on), renewable generation still presents a tremendous challenge.

California's Renewable Energy Policies

California has positioned itself as one of the leaders in the transition towards renewable energy. The California Global Warming Solutions Act of 2006, also known as AB 32, created aggressive goals for GHG reductions which, in turn, meant ambitious goals for the energy transition in the state. AB 32 required California to reduce its greenhouse gas (GHG) emissions to 1990 levels by 2020, a reduction of approximately 15% under a "business as usual" scenario (Regele, 2013). Part of California's strategy for reaching these levels of GHG emissions is through its Renewable Portfolio Standard (RPS) program. The current goal for the state's RPS, revised in 2010, is to have 33% of its electrical production from renewable energy sources by 2020. Additionally, new bills introduced to California legislation in 2015 show emerging interest in expanding the RPS situation farther into the future, to around 50% renewable energy by the year 2030 (Regele, 2013) (Mathieu et al., 2015).

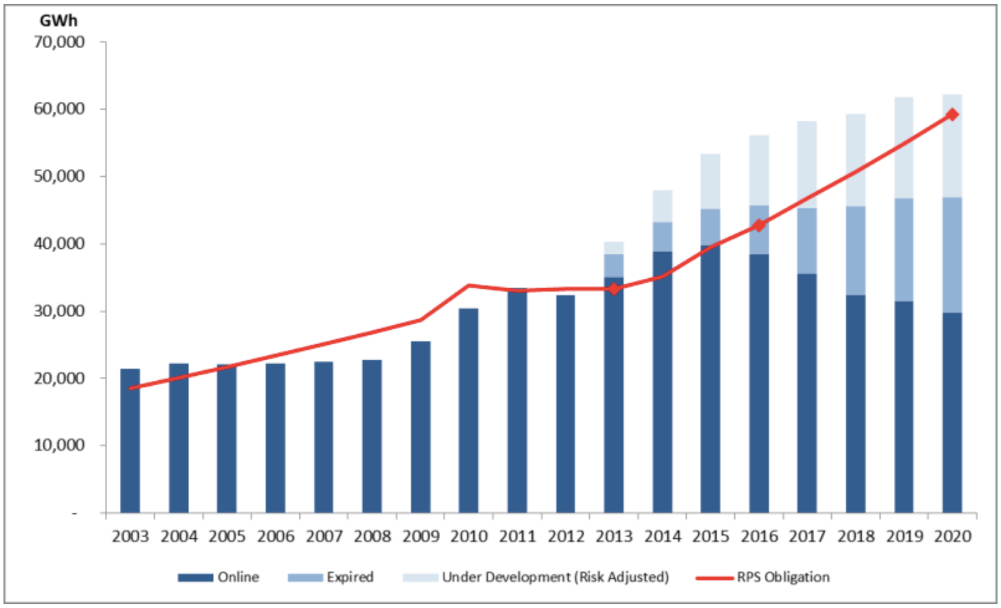


Figure 2: California's future RPS obligations through 2020

California is by no measure the current leader in renewable energy production. Some European countries already have much higher RPS. Germany, for example, generated 5% of its electricity from solar in 2012 and generated 22% of its electricity from renewables. In Spain, renewable energy represented 24% of total generation in 2012. Yet, the amount of intermittent renewable production in California's RPS program makes it unique. California has plans for heavy reliance on almost entirely wind and solar, two of the most intermittent renewable sources. Some countries such as Norway and New Zealand have served almost 90% of electric load with renewables by counting large hydroelectric resources. However, hydropower is one of the least intermittent renewable sources as it has a steady supply of power, and does not even count towards California's RPS (E3, 2014). This distinction is important because it is the intermittent nature of the renewable energy production that creates such difficult challenges in matching supply and demand. California intends to have 15% of electric load served by wind energy, and 28% served by solar energy, a much higher penetration of wind and solar than has ever been achieved anywhere in the world (E3, 2014). Denmark led the world in wind production in 2012 with 30% of its total electricity, yet the country's tiny size (coupled with the fact that it sells much of its wind power to the rest of Europe) makes it difficult to compare to California (E3, 2014).

While no country has served 40 or 50 percent of its load with variable wind and solar resources, California is not alone in considering potential futures with high renewables. Many other countries and jurisdictions have pointed to the need to decarbonize the electricity sector as a key strategy for achieving large reductions in greenhouse gas emissions (IEA, 2014). Most states in the U.S. have adopted RPS policies, as well as some European and Asian countries. Many of these areas, such as Germany, Finland and Hawaii, have adopted RPS policies that are more aggressive than California, but still do not compare to the Golden State either because of their reliance on non-intermittent renewables or their different in market size (Wiser et al., 2005). Consequently, California will be confronted by unique challenges that have not been experienced by the rest of the world, and is thus an interesting case to study for V2G integration (CAISO, 2015).

As CAISO is responsible for maintaining the grid in a reliable manner, it must deal with the added challenges that renewable energy presents. While there are a number of different operational issues with high intermittent renewable penetrations on the electric grid, two challenges have been discussed as the most significant for CAISO: frequency regulation and renewable overgeneration.

Frequency Regulation

As discussed previously, the grid must constantly be in a state of supply and demand equilibrium. Grid operators deal with the long-term variability in both supply and demand through advanced forecasting and subsequent generation response. Along with being variable day-by-day, solar and wind are highly volatile on a second-to-second basis. The increased likelihood of very short-term deficiencies and excesses of production from intermittent sources necessitates different measures. This requires that other generation or energy storage resources instantaneously compensate for these renewable-induced perturbations to maintain the precise, moment-to-moment matching of supply and demand.

Within energy markets, there are specific short-term compensating services that exist for this reason, referred to as "regulation" services. These services are meant to correct short-term, intra-day unpredictable fluctuations in the energy system, and stand in contrast to other grid services that deal with longer-term energy needs. Frequency regulation is the service that maintains the grid at a constant frequency of 60 Hz in order for the grid to function properly (Kirby, 2005). Figure 3 shows the typical fluctuations of frequency regulation around the electricity supply curve on a given day in California.

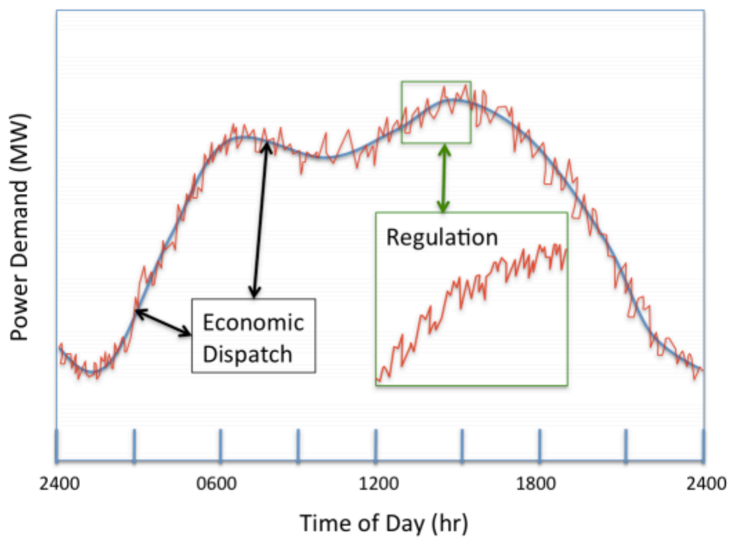


Figure 3: Frequency regulation demand by time of day

In order to maintain frequency at a safe and reliable point, CAISO sends out fluctuating frequency regulation requests in intervals generally between 5 seconds and 1 minute. Supply must then be varied, either by taking electricity off the grid or by putting more on in order to keep the frequency at 60 Hz. Any variation more than approximately .05 Hz in either direction can lead to electricity brownouts and blackouts (Kirby, 2005). Contracted generators, generally thermal generation plants, are expected to respond to the regulation request in very limited time frames and vary their supply. "Regulation up" describes frequency regulation where electricity is being added to the grid in order to meet increased demand, and corresponds to upward sloping moments of the red line in Figure 3. "Regulation down" describes the process of lowering supply, either by turning down a generator or storing excess electricity off the grid, and can be seen by the negative sloping areas on the graph.

Regulation services are one of five system services that are collectively known as "ancillary services". Ancillary services in the electric utility industry are defined by the Federal Energy Regulatory Committee (FERC) as any service that is necessary to support the transmission of electricity from seller to maintain reliable operations of the transmission system (Zhao et al., 2015). Other ancillary services cover a wide range of electricity services, such as operating reserves, which are meant to respond in case a generator goes down or there is another supply disruption. However, frequency regulation is an ancillary service that is most severely affected by high renewable supplies, since it deals directly with electricity fluctuations and intermittencies (Bevrani, Ghosh, & Ledwich, 2009).

The effects of intermittent renewable integration on frequency regulation can be seen in small measures today, and are projected to increase. A study in 2010 from the National Renewable Energy Laboratory found that in ten cases of renewable energy additions to the grid, the frequency regulation requirement on average went up by approximately 100% (Denholm, 2010). Bevrani, Ghosh, & Ledwich (2009) simulated increased RPS and ancillary services requirements and found that for RPS thresholds of approximately 30-40%, the frequency regulation requirement begins to climb at even higher rates (2009). One study found that 6.6 MW of additional frequency regulation capacity must exist per 1000 MW of installed wind power to keep the correct frequency, evidence that California is likely to see increased regulation needs in the future (Ackerman, 2005).

Renewable Overgeneration

One of the most discussed operational issues of an increased RPS in California is renewable overgeneration. Overgeneration occurs when the supply of renewable energy exceeds net demand for a certain period of time, where "net" demand means the level of consumer demand not being served by all the other production resources (E3, 2014). The reason overgeneration is such a difficult issue to solve has to do with the timing of solar energy during the day, as well as the timing of "peak power" – when Californians

demand the most electricity (E3, 2014). Since solar energy occurs only during the sunny hours of the day, thermal generation must still be available to provide energy when the sun isn't shining. However, thermal generators cannot be turned off completely and then quickly restarted. Instead, these generators can only be turned down to minimum production levels on the order of 10-20% of their maximum output levels (Cochran, Lew, & Kumarb, 2013). This results in a concept known as "the minimum generation requirement". This is the total sum of the minimum production levels of all generation that must remain operating in order to meet the increase in generation needed when the renewable generators ramp down (e.g., as the sun goes down in the afternoon). This minimum level of thermal generation can be seen at point **2** in Figure 4. The maximum speeds that these generators can be ramped up and ramped down, which correspond to Points **1** and **3**, actually dictate this minimum level of thermal generation. These maximum ramping speeds force thermal generation plants to maintain a level of generation that is high enough for the generation plant reach peak demand (point **4**) later in the day. Thus, ramping speeds, the "height" of peak power in the evening, and the amount of renewable generation required under the RPS all determine the amount of renewable overgeneration.

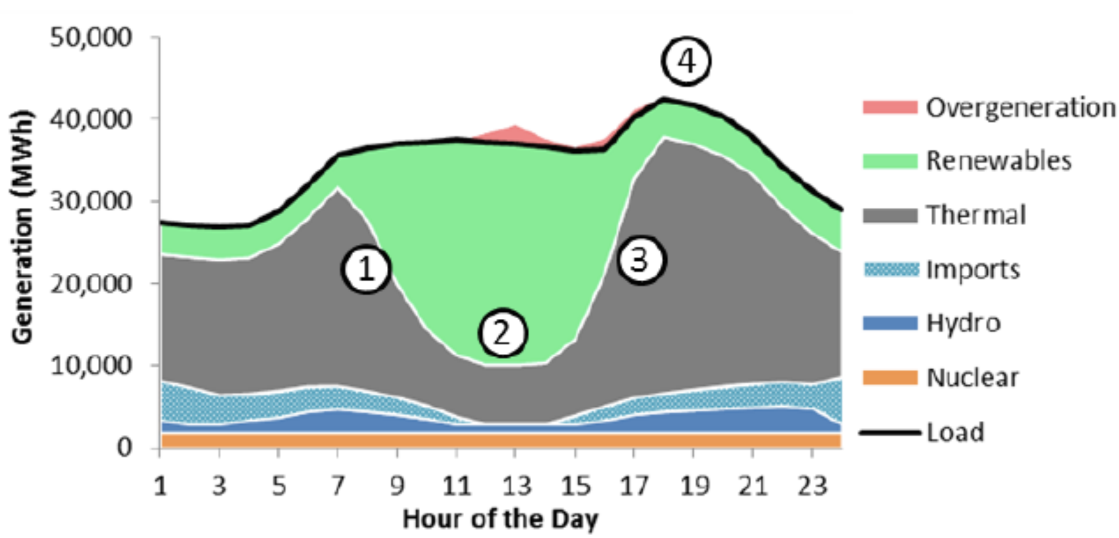


Figure 4: Overgeneration at 33% RPS

The figure above shows the small amount of overgeneration that is predicted to occur at a 33% RPS. Moving past that standard to 40% and 50% RPS dramatically increases the amount of overgeneration that occurs with the addition of solar energy onto the grid. The figure below shows, in red, the overgeneration under a 40% RPS.

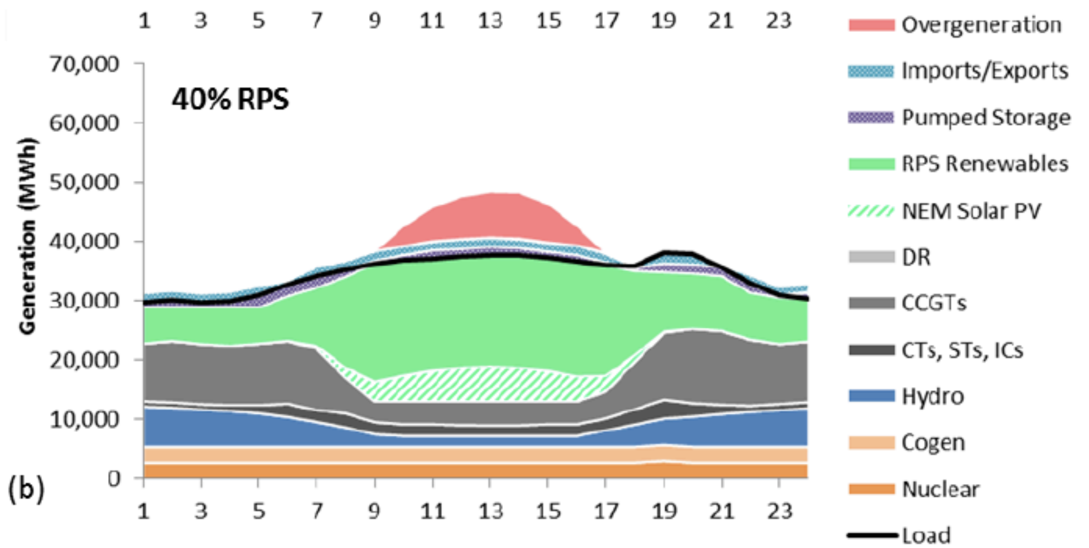


Figure 5: Overgeneration at 40% RPS

While solar energy only increases by approximately 20% in these two diagrams, overgeneration increases by over 500%, from 190 MWh to 2,000 MWh. E3 estimated that with an RPS of 40%, the goal for 2025 in California, overgeneration could occur 750 hours per year, which corresponds to almost 9% of the year.

Overgeneration is not just a theoretical issue that may affect the grid in the future – it can actually be seen in small quantities today. In Texas, where wind power is the dominant source of renewable energy, the grid had a bout of renewable overgeneration in April 2008 when wind was overly active. During this period, renewable curtailment had a price of $30-$40/MWh, meaning that the grid operator had to either pay utilities that price to curtail electricity generation or pay other grid operators to take the energy off the Texas grid (Sioshansi & Hurlbut, 2010). As a comparison, the whole electricity price during this period was approximately $20/MWh, meaning that the grid operator had to pay roughly two times the price of electricity to *not* have energy during those times.

Denmark, another area with large percentages of wind power, has experienced similar curtailments as well (NREL 2010).

In California, overgeneration has so far occurred only in one period, from February to April of 2014, for a total of only six hours. However, recent signs point to CAISO and California's generators preparing for more frequent periods of overgeneration challenges. To help address this challenge, the price floor for electricity was recently lowered from -$30/MWh to -$150/MWh, which represents the price that the grid operator is able to pay generators to curtail their generation to avoid overgeneration (Howarth & Monsen, 2014). In addition, California has announced plans to lower to floor even further to -$300/MWh in the near future (Howarth & Monsen, 2014). This move is evidence that CAISO is preparing for a more serious overgeneration problem and expects to have to increase economic incentives to reduce overgeneration.

Overgeneration presents two main issues for California. First, there is economic inefficiency involved in curtailing renewable generation to reduce overgeneration. Solar and wind power have essentially zero variable costs, so any time that generation is curtailed or is sold to other grid operators, there is missed economic opportunity. Second, renewable curtailment leads to more difficulties in reaching the prescribed RPS percentages. If a certain amount of renewable energy cannot be distributed and sold in a grid, this means that the same amount of renewable energy must be supplied at a different time – otherwise, renewable supply percentages will fall short of the RPS goal (Howarth & Monsen, 2014).

Non-Storage Alleviation

Even without energy storage, some steps can be taken on the electricity generation side that will limit these operational difficulties of increased renewable penetration. For example, diversifying the type and number of renewable energy generators could lead to less variability in the electrical supply. Energy and Environmental Economics Inc. (E3) shows in its 2013 study how renewable diversification leads to less random power

shortages from natural conditions (E3, 2014). The report finds that a combination of wind, solar, and nuclear power could potentially lead to less operational challenges on the electrical grid, although too much diversification could raise costs – since sunshine is the dominant natural energy source in the state, solar power on average is more effective than other renewable resources (E3, 2014).

Another potential option to help reduce renewable overgeneration is demand side management, meaning the grid operator has some control over the electricity demand quantity at any given time. There are two main ways that this could be accomplished. The first is to increase control of in-state demand through economic incentives for electricity users. For example, CAISO could subsidize electricity prices during the middle of the day to make costs lower in order to increase demand during this period (Panfil, 2012). A second way to manage demand is to increase the size of potential electricity exports to other regions. With a bigger pool of outside regions to which to export electricity, CAISO has more flexibility in shipping out excess supply (E3, 2014).

No matter how diversified the renewable portfolio ends up being, or how manageable demand is, matching supply and demand through the grid will still be a tremendous challenge. It is likely that CAISO will undertake some of these measures to help decrease the challenges and economic losses, but the extent to which these practices will help is unclear. Battery technology, and specifically V2G, has the potential to be a constructive part of the portfolio of solutions for addressing both of these issues.

Energy Storage for Frequency Regulation

Batteries are an effective way of dealing with regulation services. Unlike traditional generators, which provide large quantities of energy capacity to meet large-scale energy demand, regulation services are short-term electricity services that deal with relatively smaller amounts of energy. Thus, these services rely much more on *power* capabilities (energy over time), rather than total energy capacity. While theoretically batteries could provide many other ancillary services, the advantage of batteries for regulation lies in this

power capacity aspect (Chhabra et al,, 2011). Technologies such as lithium ion batteries, which have limited energy content but can very quickly transfer that energy, are well suited for frequency regulation. Batteries could hypothetically provide other ancillary services to the grid, but in recent studies, lithium ion batteries have been shown to have power capacities in excess of the electricity distribution lines themselves, meaning that energy can be transferred both to and from a battery at the maximum allowable rate of the grid (Chhabra et al., 2011).

Another reason that batteries are well suited for frequency regulation lies in the mean-zero oscillation property, meaning that there are roughly equal amounts of "regulation up" as there are "regulation down" (Petit & Perez, 2013). The reason that this property is critical is that batteries are limited by their total energy capacity, and cannot discharge past 0% (completely empty) or charge past 100% (completely charged). For instance, if frequency regulation requires continuous "regulation up" services, the battery would quickly discharge all of its energy and no longer be able to provide additional services. By maintaining a roughly mean-zero oscillation, frequency regulation enables vehicle batteries to consistently charge and discharge energy for regulation up and down for much longer periods of time. Figure 6 shows a closer up image of frequency regulation on a typical day in the Eastern U.S., and the roughly equal amount of area above and below the 0 MW regulation line show the mean-zero oscillation property.

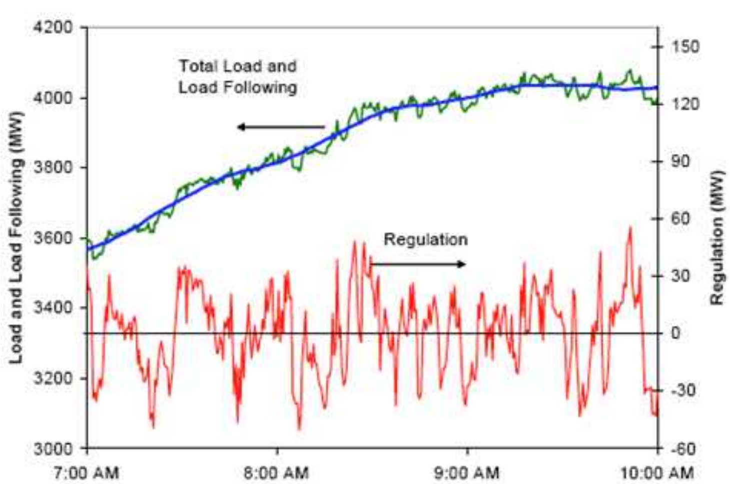


Figure 6: Close up of regulation services

What exactly would frequency regulation look like for a vehicle battery in V2G? In this scenario, the vehicle is constantly charging and discharging while parked and plugged in. "Regulation up" corresponds to the vehicle discharging its battery, whereas "regulation down" is accomplished by charging the battery. Theoretically, the vehicle could perform this service for as much time as it is parked. However, Petit & Perez (2013) found that regulation services are not always perfect mean-zero oscillators. Thus, an error term will be added in the revenue section to account for the fact that some vehicles may reach full or zero capacity during frequency regulation. As with other resources that provide frequency regulation, batteries have unique costs associated with using them for regulation services. The main cost for regulation services is the increased wear on batteries that lowers their lifetimes, which will be discussed in more detail later. In order for storage to be a viable option, revenues from regulation services must outweigh these costs.

Energy Storage for Overgeneration

Energy storage, and specifically V2G, is also well suited for helping to alleviate some of the renewable overgeneration in California. One important factor to consider when using energy storage for overgeneration is whether that energy can be used later on. This is critical, as the battery must be able to discharge to perform storage at a later time, and also because the energy is wasted if it can't be utilized. The usage of this energy for vehicle batteries is obvious – to power the vehicle for driving.

A typical scenario would be for a driver to commute to work in the morning, therefore draining his/her battery a specific amount. Then, while parked from the hours of 9am-5pm, the driver could absorb overgeneration by charging the remainder of their battery, while getting paid the market rate for overgeneration storage. Overgeneration storage can be thought of simply as "paid charging" for these vehicles. The driver would then have a full battery charge that he/she could use to commute home and also commute to work the following day.

Renewable storage differs slightly from frequency regulation as a V2G service because it is not guaranteed. As E3 (2014) pointed out in their study, renewable overgeneration is only likely to occur in winter months where the daytime load is not as high. The data section of this paper will detail the forecasted amounts of renewable overgeneration and adjust the potential profits based on those numbers. However, it is assumed that vehicles can switch back and forth from providing frequency regulation and overgeneration storage. While this would require advanced smart-grid technology with perfect information on vehicle charge levels, etc., providing both of these services is theoretically possible. Other assumptions of the V2G scenarios will be explained in the next section.

V2G: Implementation and Economics

Business Plan

Implementing V2G requires a sound business plan, with scenarios that can provide profit to all parties involved. Rather than having individual vehicles provide commercial level services through V2G on their own, a more effective way to carry out these V2G services is through an Electric Recharge Grid Operator, or ERGO (Anderson et al., 2009) (Peterson et al., 2012). ERGO is a term introduced recently that describes a system in which one single operator has control over a fleet of vehicles, integrating them all into a generation resource that provides services to the grid. Generally, the single operator is a parking garage or structure that already has the ability to house several parked cars.

The reasons for using a fleet of vehicles for V2G, rather than individual vehicles (such as providing V2G services from a household charger) are two-fold. First, CAISO and other system operators generally require a certain amount of power for any single generating unit that wants to interact with the grid. In 2007, CAISO raised their power block requirement to 1 MW, meaning that any unit that wants to interact with the grid

must have a power capacity of at least 1 MW (Kempton, Tomić 2007). 1 MW is equivalent to the power of between 15-80 EV batteries[1], which is the minimum requirement for a vehicle fleet in order to fit into these electricity market rules. The second advantage of using a fleet of vehicles is that it creates some flexibility in providing the total power capacity. In the frequency regulation market, generators are required to state how much power capability they are going to provide in a day-ahead market. By having many vehicle batteries available for an ERGO to supply to the grid, if one or two vehicles aren't available for any reason, the total power capability is not greatly affected.

Although much of the discussion around an ERGO system has been theoretical, there have been a few attempts at integrating an actual system. Better Place, an Israeli-based company, deployed about 20 bi-directional V2G stations across the country by 2012, with a central operator controlling the fleet of vehicles. However, financial difficulties and mismanagement led to the company going bankrupt in 2013 (Budde-Christensen, 2013). Denmark, a country with large amounts of wind energy, has also begun implementing V2G stations in the country. A full business model piloted by *DONG Energy* shows plans for increasing the scope of the project through 2020 (Pillai & Bak-Jensen, 2011).

One critical component of the ERGO model is the smart-grid (part of a broader concept known as the Internet of Things[2]). V2G using fleets of vehicles requires a certain level of smart-grid and operational technology that can enable information about vehicle charge levels, grid services, and prices freely between all vehicles and the operator. Some authors have detailed these challenges, but also have noted that trial V2G runs show that there is real life feasibility (although high costs) (Guille & Gross, 2009) (Petit & Perez, 2013). Rather than going into more detail about these challenges, they will simply be left out of the equation.

[1] Given the range of between 30 kWh and 80 kWh, discussed in more detail in the data

[2] See Atzori, Iera, & Morabito (2010) for a comprehensive explanation of the Internet of Things

The ERGO model has two main parties involved – the business, such as a parking garage, who makes the initial investments in V2G infrastructure, and the individuals who own the electric vehicles. Both parties are invested in the V2G project, and as such both parties need economic incentives. This next section will describe how revenues and costs will be calculated for V2G.

Cost and Revenue Equations

While vehicles are plugged into the grid through V2G enabled connections, they are either receiving electricity or putting it back into the grid. This creates both revenues and costs for the vehicle, which will be outlined in this section. The revenues represent the additional benefits that the grid receives from the services of the vehicle battery, while the costs constitute both the infrastructure required to undertake V2G, as well as the added strain on the vehicle battery.

Frequency Regulation Equations

The economic value of V2G frequency regulation follows the typical form of any profit equation – revenue minus costs. This can be represented as:

$$\pi_R = r_R - c_R$$

Profit for frequency regulation, π_R, is the revenue created through the regulation service, r_R , minus the cost that the vehicle owner will incur, c_R.

Revenue:

Frequency regulation generates revenue because it adds or extracts critical amounts of energy from the grid in order to stabilize the grid. The revenue, just like for any electricity service provided to the grid, is simply the product of the total electrical energy and the marginal price of the electricity. In addition, since energy is equal to the amount

of power multiplied by time, it can also be depicted that way in equations. This is especially useful because oftentimes prices and requirements are set forth by the power, not necessarily total energy. Revenue can thus be written as:

$$r_R = p_e \cdot P_R \cdot t_R$$

where p_e is the price of the electricity supplied, P_r is the power supplied by the vehicle for regulation, and t_r is the amount of time that the regulation power is flowing.

For frequency regulation services in California, the payment is actually derived from two sources: a "capacity payment", and a "mileage payment". The capacity payment is paid to a regulation provider for the maximum potential energy that that provider may have to supply for the regulation time duration (whether or not that electricity is actually used). The main reason for this payment has to do with how frequency regulation has been traditionally provided by power plants. Generally, electricity providers must ramp down some of their base-load combustion generators so that they have capacity available to sell in the regulation market. The opportunity cost of setting aside energy for frequency regulation is the foregone revenue from operating those generation resources in the wholesale electricity market (Kirby, 2005). [3] Thus, capacity payments often are similar to the price of electricity in base-load power markets.

The mileage payment, on the other hand, is the *actual* amount of electricity that is used for regulation up and down in a specific time period, and has a different price than the capacity payment. While the capacity payment is one single cost for total regulation requirement, the mileage payment can be different for both regulation up and down (CAISO, 2015). This means that there can be a different price associated with a vehicle charging its battery, and a vehicle discharging its battery. Thus, a more comprehensive

[3] Kirby also notes that increased renewable penetration can actually depress the costs of regulation services. This is because renewable energy causes many thermal plants to have to ramp down anyway, diminishing the opportunity cost of supply regulation. Indeed, CAISO data from their OASIS website shows that capacity payments are slowly lowering.

revenue equation takes into account the different types of energy supplied, and the separate prices that correspond with each type. This can be written as:

$$r_R = (p_{cap} \cdot P_R \cdot t_R) + (p_{RU} \cdot P_{RU} \cdot t_{RU}) + (p_{RD} \cdot P_{RD} \cdot t_{RD})$$

where p_{cap} is the price of the capacity payment, and p_{RU} and p_{RD} are the prices of regulation up and down. In addition, this equation has different P and t terms for the power and time of total regulation ($_R$), regulation up ($_{RU}$) and regulation down ($_{RD}$).

Finally, a "fudge factor," or error term, can be added and multiplied by the mileage payments to represent the difference in ideal revenue and actual revenue. One of the sources for this difference lies in the fact that frequency regulation does not always have equal parts regulation up and regulation down, and thus will eventually lead the battery SOC to be completely charged or completely discharged, which would discontinue frequency regulation. Another source of error is the loss of electricity through transfer or through line losses. This loss will affect the total energy that is provided through frequency regulation, and thus will decrease revenues by a certain amount.

Costs:

The main costs for providing frequency regulation through V2G are the capital costs associated with providing V2G functionality, and the additional wear on the vehicle battery from increased cycling. The capital cost for V2G mainly stems from the special bidirectional charger and wiring that V2G requires so that energy can flow both in and out of car batteries.

Batteries have specific lifetimes that depend on the number of charge cycles (charging and discharging a battery) that are completed. More specifically, the lifetime depends on both the number of charge cycles as well as the total depth of discharge that each cycle goes through, meaning how close to fully charged or fully discharged the battery gets each cycle (this will be explained further in the data section). Any V2G

service that causes the battery to charge and discharge *in addition* to regular driving patterns will further reduce its overall lifetime. These additional charge cycles cause an increase in how frequently the vehicle battery must be changed. These battery wear costs can be converted to initial capital costs by calculating the present value of the additional charges from V2G. By lowering the lifetime of the battery and moving the impending battery replacement closer, V2G raises the present value of battery replacement. The battery cost prevent value can be calculated by:

$$PV = \sum_1^n \frac{c_b}{(1+r)^{t*n}}$$

c_b is the cost of the vehicle battery, and t is the lifetime of the battery if it were only used for frequency regulation (this represents just the added battery depreciation of V2G, which is the difference in battery lifetime under regular driving patterns and through V2G), and n represents the nth time that the battery has had to be replaced since the beginning of V2G (i.e. n=2 means this is the second battery replacement).Therefore, $t * n$ is the number of years into the future that the battery has to be replaced. The value of t is determined by dividing the total number of charge cycles by the number of V2G added cycles / year. The value of n is determined based on how many times the battery must be replaced in the V2G timeframe, and is determined on a case by case basis. For example, a vehicle providing more hours of frequency regulation per year will need battery replacements more often in a certain timeframe than one providing less regulation.

One complicating factor of this present value calculation is that the vehicle battery may be in the middle of its lifetime degradation cycle when the timeframe ends. This likely will still translate into a future cost for the vehicle owner either by 1) translating to a lower vehicle value is the owner decides to sell his/her car with a degraded battery; or 2) requiring the owner to replace his/her vehicle battery sometime after the V2G timeframe. For simplicity, it is assumed that the percent of battery degradation for the final battery translates to an equivalent percent cost of the battery. For example, if the final battery is 60% through its total lifetime, the cost at the end of the V2G timeframe is 60% * the cost of the battery.

Total costs are the sum of the initial investment costs and the present value of battery replacements.

$$c_R = c_i + \sum PV\,(C_b)$$

c_R is the total cost of providing frequency regulation. c_i is the intial investment by the parking garage for charging stations and wiring, and the last term represents the battery wear costs for the vehicle owner.

Overgeneration Storage Equations

Overgeneration storage is a much different system than frequency regulation in terms of the benefits that is supplies to the grid and the type of service performed by the vehicle battery. To store overgeneration, a parked vehicle could simply charge its battery from the current SOC to the maximum SOC once daily. The revenue would equal the available capacity in the battery to charge times the price that the utilities are paying for overgeneration storage. This can be represented as:

$$r_o = p_o \cdot E_{pc}$$

r_o is the total revenue from overgeneration storage, p_o is the price of renewable curtailment, and E_{pc} is the available capacity percent in the battery post-commute, which is the maximum battery storage minus the amount of charge lost while driving to work. Given that the average commuter drives 13 miles each way to work, and the 2014 Nissan Leaf has a range of about 100 miles, E_{pc} is simplified to .25 of battery energy capacity (Kelly Blue Book, 2015).

Costs for overgeneration storage would only be the initial infrastructure investment by the business. Overgeneration storage is simply charging the battery for the vehicle

owner's driving needs, which would have happened anyway were it not for the V2G service. Overgeneration storage therefore adds no additional battery wear to the vehicle battery and has no costs associated with that.

Revenue/Cost assumptions

For simplicity, this model assumes that costs and revenues scale linearly, and thus fleet size for each V2G site does not matter. Realistically, this assumption might not hold – the size of the vehicle fleet for the V2G operator is likely important (Kempton, Tomić 2005a). A parking garage that manages a fleet of 1,000 vehicles for V2G could be less costly on a per vehicle basis than a garage with 20 vehicles, mainly because of the upfront costs associated with V2G management and operations. Each V2G site would have costs associated with personnel and technology that would need to simultaneously manage the charging of each vehicle battery with the current information about grid service requirements. Once this technology is installed at each V2G site, the marginal cost of managing an additional vehicle would theoretically decrease. However, this study does not take into account many of these upfront costs that potentially would scale non-linearly with fleet size, as they are widely unknown in the present. Costs that this study *does* take into account, such as the vehicle battery and charger, are often quoted as costs per individual vehicle in literature. This literature gives little information on how these costs might scale.

On the revenue side of the V2G profit equation, this simplified model holds, as payments for electricity services actually *do* scale linearly. For instance, doubling the amount of electricity a generator supplies also doubles revenues, since prices stay constant. This study will therefore perform profit analysis for different V2G scenarios based on single vehicle revenues and costs.

Data and Model Specifications

The main source for data on electricity prices is CAISO's 2014 Long Term Procurement Plan (LTPP) study (CAISO, 2015). This study used comprehensive software and modeling to determine electricity prices and quantities for multiple renewable standard scenarios in the future. One of these models was a 40% RPS standard for the year 2024, which was chosen for this study. The main reason for choosing this scenario is because many of the affects on the grid, such as increased renewable overgeneration and frequency regulation become amplified at around the 40% RPS mark. In other words, this renewable portfolio percentage is when the largest operational challenges to the grip begin to amplify rapidly. This would create an ideal time for V2G implementation.

The data includes a vast array of predicted electricity prices, including for all ancillary services such as frequency regulation, even at the hourly level. It also includes predicted quantities for these services across the state and in specific regions. The study also predicts the amount of renewable storage that is expected to occur in 2024, as well as an estimate of the price that utilities are willing to pay to prevent curtailment. It is important to note that much of the data has large fluctuations by time of the year, mainly because renewable generation also fluctuates during the year. For simplicity, prices were averaged across all times over the course of the year. In addition, the minimum prices in the data set will also be used as yearly averages in order to provide conservative revenue estimates for the business. The data did not provide intra-day prices for frequency regulation or overgeneration storage, which is another simplification assumption as prices are likely to change from day to night in actuality.

Price data is summarized in Figure 7 at the end of this section[4]. Regulation up mileage prices are approximately twice those of regulation down prices, while both are highly variable by month. Also of note is that both regulation capacity payments and overgeneration storage prices are the same across the entire year in the data set, with

[4] All data is in 2014 US Dollars, so no inflation calculations were needed

regulation capacity payments set at $0.04/kWh and overgeneration storage at $.3/kWh. Many of the methods that CAISO used to predict these prices are unknown, so it is difficult to understand how this data was obtained. One interesting aspect of the overgeneration price is that it corresponds exactly to the new price floor that CAISO set for negative energy prices in 2014. CAISO may believe that overgeneration during this period will be priced at this price floor of $.3/kWh.

While frequency regulation is assumed to be a 24/7 service, meaning vehicles can constantly earn revenue from providing the service, overgeneration storage is not. The data on overgeneration storage is detailed in the Appendix. Overgeneration occurs much more often in the winter and early springs months than in the summer. On average, it occurs about 10% of all days in the year, which is similar to CAISO's earlier estimate. Thus, a multiplier of .1 will be used on all annual revenues for overgeneration storage because it can only be used as a V2G service 10% of the year.

The data that is specific to vehicles and battery/grid technology were gathered from similar studies either on V2G technology or electric vehicles. For each metric, such as type of vehicle or cost of infrastructure, data was selected based on two lines of reasoning: 1) Does this data represent current technology or pricing? and 2) What are the reasonable data ranges that someone trying to implement V2G might expect? The first question is used to insure that the numbers are all feasible and could be implemented for V2G today. The second question is used to determine which variables might require "sensitivity checks". In this study, sensitivity checks mean determining how the revenue or cost figures change based on changes in specific variables. Since in many cases there are ranges for electricity prices or technology specifications, using a span of numbers where appropriate is important to understand the low and high-end estimates. These sensitivity checks will be explained for each metric in this section, as well as in more detail in the results section of the paper. All data on these metrics are also summarized at the end of this section.

For example, in order to determine the size of the vehicle battery for the revenue estimates, the current electric vehicle market in the U.S. was examined. Two of the most popular EV models today are the Tesla Model S and the Nissan Leaf, so these vehicles were chosen to represent what would most likely be used in V2G (Kelly Blue Book, 2015). These two EVs also represent a good range of battery sizes in the EV market. The Nissan Leaf's battery has an energy capacity of 30 kWh, which is on the low end of EV battery spectrums today, while Tesla's Model S 85 kWh battery is one of the largest. Thus, these two vehicles represent feasible technology as well as a reasonable range of battery sizes for revenue calculations.

Other important metrics include electricity transmission constraints, battery-wear costs, and infrastructure costs. The electricity transmission speeds both in and out of the vehicle are critical in determining how much electricity the vehicle can provide and store. EV chargers that connect the vehicle to the grid are one determinant of charging speeds. These chargers are grouped into different power "levels" based on speeds. Today, common chargers include Level 1, mainly residential charging stations, and Level 2 in commercial buildings. Level 2, which has a power capability of 20 kW, has been used in V2G calculations in other literature, and is the most likely type of charger for V2G today (Pillai & Bak-Jensen 2011) (Peterson et al., 2012). Level 3 charging, which can reach transmit power at speeds of 100 kW, are beginning to surface in commercial areas but are still being developed (Yilmaz & Krein, 2013).

Battery wear costs depend on the cost of the battery, and the battery lifetime given V2G requirements. Current costs of EV batteries are approximately $100-$300/ kWh (Han & Han, 2013). However, battery costs have been declining at 8% annually and are predicted to continue falling. Thus, $100/ kWh is a good estimate of the cost of an EV battery given the future of battery technology, as well as the fact that changing a vehicle battery is often less expensive than the first installation because some of that cost includes the battery management technology which does not need to be replaced (Han & Han, 2013). $200/kWh will also be used as a high-end cost estimate given that businesses also might want a conservative data point.

Battery lifetimes depend primarily on the depth of charge/discharge of the battery during each charge cycle, as well as the frequency of these charging cycles. For instance, a battery that is charged to only 3% of its total capacity, and then discharged, can last for approximately 1,000,000 similar charging cycles. On the other hand, when a battery is fully charged and discharged, the number of cycles in its lifetime drops to around 3,000 (Kempton & Tomić 2005). The exponential relationship between lifetime and depth of discharge and lifecycle can be seen in the appendix.

Han & Han (2013) tested the change in a battery's state of charge (Δ SOC) during frequency regulation usage. They found that because of the constant change in regulation signals between regulation up and regulation down, the battery charge level rarely moved more than 0.5% in either direction. Given this information, the depth of charge/discharge for frequency regulation is assumed to be 1% given that the battery might move 0.5% both up and down. The precise number of cycles in a battery's lifetime given 1% Δ SOC was not tested in this study. However, a rough estimate given the exponential relationship between Δ SOC and battery lifetime is 3,000,000 cycles (three times the number of cycles at 3% Δ SOC). As discussed previously, using V2G for storing renewable overgeneration in theory requires no additional battery cycling than a non-V2G user with traditional driving patterns. This is because a vehicle storing overgeneration simply charges its battery once, to 100% SOC, and then uses that battery life for driving later on.

Infrastructure costs for V2G are difficult to estimate. Many of the V2G projects currently in testing use custom-built V2G infrastructure and don't disclose the costs of charging and communication equipment (Pillai & Bak-Jensen, 2011) (Brooks, 2010). Yilmaz & Krein (2012) used data from SAE International and Ideal Power, two companies working on developing bidirectional V2G equipment, and concluded that Level 2 charging infrastructure is approximately $1,000-$3,000, and Level 3 charging anywhere from $90,000-$160,000 per unit. Previous studies on V2G have ruled out Level 3 charging because of the immense upfront costs as well as the technology uncertainty and challenges that arise from these new chargers (Peterson et al., 2012). Initial

calculations also show that the increased revenues from higher charging speeds will not be enough to make up for the high initial costs, so Level 3 charging is ruled out for this study.

Another metric that must be determined is the discount rate. The discount rate will be used for discounting future battery costs as well as discounting future cash flows from V2G. Miller (2014) performed a similar business plan study for green roof implementation and used Treasury bill rates to determine a discount rate of 4% for his project. Given the fact that this V2G business scenario is likely less risky given the contracts between vehicle owners and garages, as well as the fact that electricity prices are fairly sticky (i.e. do not change rapidly), a discount rate of 3% seems reasonable.

Finally, the error term, or "fudge factor" applied to all V2G revenues was determined to be .9. This number takes into account two potential revenue losses: first, frequency regulation has approximately a 5% chance of not being a mean-zero oscillator, which would completely charge or discharge a battery and render it unable to collect revenue (Kirby, 2005). Second, Kempton & Tomić (2005b) found electricity line losses for V2G to be approximately 5%. Together, this creates the .9 error term.

	Average	Minimum Month	Maximum Month
Regulation Up Mileage ($/kWh)	0.0221	0.0155	0.0331
Regulation Down Mileage ($/kWh)	0.0111	0.0011	0.0258
Regulation Capacity ($/kWh)	0.04	0.04	0.04
Overgeneration Storage ($/kWh)	0.3	0.3	0.3

Figure 7: Price Data

Power, line (kW)	30 (Level 2)
Battery size (kWh)	30 (Leaf) / 85 (Model S)
Battery Cost ($/kWh)	100 / 200
Infrastructure Cost ($/unit)	1000 / 3000

Figure 8: Infrastructure and Cost Data

Business Scenarios

One important aspect of the V2G model is the timeframe of operation for the business and the individual. The assumption for this study is that each V2G fleet operates for a total of 8 years, which would be the complete contract time between the garage and vehicle owner. This timeframe was chosen for two main reasons. First, 6-8 years is the average timespan that an individual owns a vehicle before changing cars (Dargay, 2007). Second, many of the V2G technologies such as bidirectional chargers and vehicle batteries, are expected to improve in the future, and prices could also change. Gao (2010) also noted that V2G chargers likely have lifetimes of around 10 years, so much of the infrastructure would need to be replaced at around 8 years anyway. Restricting the timeframe to 8 years is thus a good way to calculate profits without having to worry about many changes in these variables.

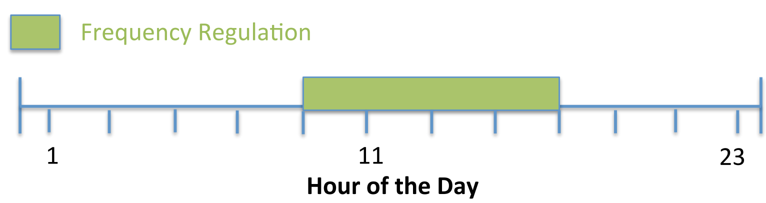
The model assumes that each parking garage operates on weekdays for 50 weeks of the year, for a total of 250 days/year. Another assumption is that each parking space with V2G infrastructure is guaranteed to be filled with a V2G enabled vehicle at the appropriate times that are laid out in each scenario. Unlike normal parking garages, whose occupancy can fluctuate depending on the day, V2G must rely on contracted vehicles being able available at the correct times. Therefore, the parking garage is assured of its revenue streams once vehicles are contracted.

Model 1: Frequency Regulation

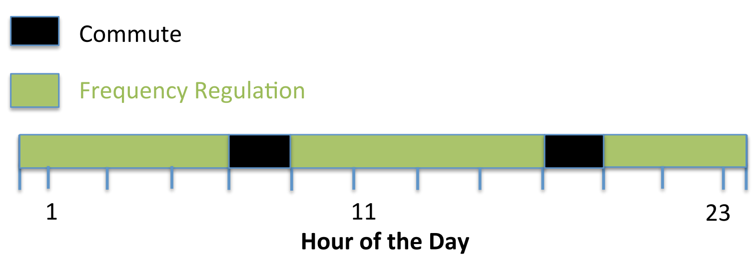
The first business model for V2G is a garage whose vehicles provide only frequency regulation services. In the first scenario, the garage would only house vehicles parked during the day while the individuals are at work. This means that the only times the vehicles would be producing revenue would be between the hours of 9 am – 5 pm (Scenario 1). The second scenario adds another "shift" of vehicles that would park in the

garage overnight. This second scenario takes into account peak commuting hours when both shifts of vehicles are likely to be driving and not parked, 7 am – 9 am and 5 pm – 7 pm, therefore not producing revenue (Scenario 2).[5] The first scenario has a daily productive time of 8 hours, while the second scenario has 20 hours of revenue-producing time. While one individual might be parked in separate garages for their workday and nighttime shifts, the assumption is that a vehicle would be able to perform both shifts, just at different garages, resulting in maximized revenues.

Scenario 1: Workday Shift Frequency Regulation



Scenario 2: Workday and Nighttime Shifts Frequency Regulation



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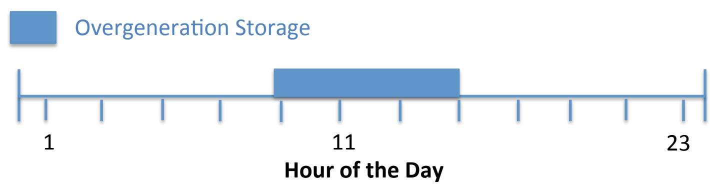
[5] See California Department of Transportation Traffic Census Program for detailed traffic volume data by hour.

Model 2: Overgeneration Storage

Providing overgeneration storage is another option for V2G equipped vehicles. According to the data, the times that overgeneration is likely to occur are the work hours: 9 am – 5 pm. Thus, a simple V2G model using vehicles only for overgeneration storage would look like Scenario 3, where vehicles parked during the daytime hours could absorb renewable overgeneration[6].

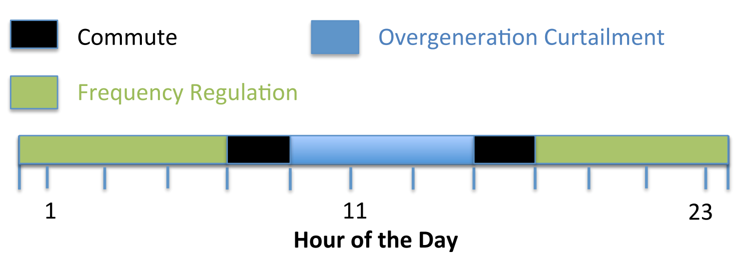
Scenario 3: Workday Overgeneration Storage



Model 3: Hybrid

Another potential model for a parking garage would be to use vehicles to provide both overgeneration storage *and* frequency regulation. This model is referred to as the hybrid model. In this scenario, the workday shift of vehicles store overgeneration (is available). After a period of commuting time, the nighttime shift of vehicles would then provide regulation services. If overgeneration is not occurring on any given day or at any given time, the workday vehicles will switch to providing frequency regulation, and the model looks exactly like scenario 2.

Scenario 4: Hybrid



[6] This scenario could only be performed when overgeneration is occurring, which is approximately 10% of the days in a year.

Results

For all of these models, both revenues and costs per year were calculated for the Model S and Nissan Leaf. These revenues and costs include both high and low estimates using the ranges of input data. Intermediate steps also included calculating the present value of battery costs for frequency regulation. This required finding the additional number of charge cycles/year that frequency regulation required, and using the Δ SOC for each scenario to calculate the battery lifetime. These intermediate calculations yield some important insight into how the Model S compared to the Leaf for revenues and costs. For both of the frequency regulation scenarios, revenues were the same for the Model S and the Leaf. This is because regulation depends only on the power capabilities of the V2G infrastructure, which was limited by the 30 kW charger, and not on the total energy capacities of the vehicle batteries. However, battery costs were higher for the Leaf under both scenarios. The Leaf's smaller battery causes frequency regulation to have a larger Δ SOC in each cycle than in the Model S. This leads to shorter battery lifetimes, and therefore greater present value battery costs. These higher costs caused the Leaf to generate less profits than the Model S.

For scenarios with overgeneration storage, the Model S also had much higher profits than the Leaf. Without any battery degradation costs, the only determinant of profit for overgeneration storage is revenue. The Model S's battery can store almost three times the amount of renewable overgeneration than the Leaf can, which creates much higher revenues for the Model S. The Model S was thus more profitable in every business scenario. This is encouraging, as vehicular battery technologies are advancing to hold even more energy, a sign that V2G has more profit potential in the future.

Finally, for each scenario, total costs were subtracted from total revenues for the eight-year period (using the 3% discount rate) to find the net benefit of each model. Calculating this total "social benefit" shows which business scenario creates the most total profit, and is an indicator of the most ideal business scenario. For these calculations,

the highest costs and lowest revenues for the Model S from each scenario were used for conservative estimates.

Figure 9 shows the total social benefits for each scenario. Scenario 2 and Scenario 4 are the only models that have positive social benefits, meaning they are the only potential scenarios that generate a profit in the 8-year time span. Scenario 1 has a negative social benefit because frequency regulation is only being provided for 8 hours a day. When frequency regulation is provided for the longer 20-hour period in Scenario 2, this generates a total profit of approximately $1,000. Scenario 3 has a very negative social benefit. This is because overgeneration storage simply occurs too seldom to generate enough revenue on its own. However, when overgeneration is combined with frequency regulation in the hybrid Scenario 4, this generates the most social profit ($3,560). Since the only difference between Scenario 2 and Scenario 4 is overgeneration on 10% of the workdays, this proves that overgeneration storage is more profitable on an *hourly* basis. The overgeneration storage price, at $.3/kWh, is more than 5 times the combined price of capacity and mileage payments per kWh for frequency regulation. Thus, combining overgeneration storage with frequency regulation so that revenue is being generated all 20 hours of the day is the most compelling and profitable business scenario.

It is also important to note that the most conservative revenue figures and the highest cost figures were used to calculate the net social profit. If, on the other hand, the highest revenue and lowest cost figures were used, this would yield an 8-year profit of over $22,000. This shows the potential for large amounts of profit for V2G when (and if) costs are on the lowest end of the spectrum and revenues are at their potential peak.

Sensitivity checks on these numbers reveal that the most important metrics for determining profits are vehicle battery size and the power capabilities of the line. If the vehicle battery were to increase to from 85 kWh to 100 kWh, net social profit for Scenario 4 would almost double to $6,200 for the most conservative estimate. Increasing the battery energy capacity has two profit-increasing effects: 1) It allows the vehicle to store more renewable overgeneration, and 2) It lowers the Δ SOC during frequency

regulation, which lowers costs. When power capabilities of the line increase, this also has a positive effect on profits. Increasing the line power from 30 kW to 40kW increases profits by $1,100. Both of these sensitivity checks are important because vehicular battery storage and transmission line power capabilities are expected to increase in the future, which will significantly increase the profit potential of V2G.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Revenue/Year ($)	1398	2940	160	3010
Total Costs ($)	10950	19653	3000	17673
PV of Total Social Profit ($)	**-1120**	**1008**	**-2865**	**3560**

Figure 9: Social Profits by Scenario

Revenue Sharing

Now that the hybrid scenario has been determined to be the optimal V2G business scenario and generates social profit, the next question to answer is how the profits will be split between the individual and the garage owner. This is important, as both parties will need a certain, reasonable level of profits to be incentivized to participate in V2G. One way to determine the most extreme values of profits for each party is set up scenarios where one party is given zero profits and the other takes all the profits. This means that in one case, the individual is compensated only enough to equal the costs of the battery wear and the parking garage takes the remainder of the revenue. In the other case, the parking garage receives revenue equaling their costs, and the vehicle owner gets the profits.

For the first case, the vehicle owners would need to receive annual revenues of $2,090 for the 8-year term, which discounted at 3% would compensate for the $14,673 present value of battery wear costs. This would leave the remainder of annual revenue, $920, for the parking garage. One meaningful measure of revenues for businesses like a parking garage is the payback period. This is the amount of time that the business can expect to break even on their initial investments. With $920 in annual revenues, discounted at 3%, the parking garage would have a payback period of about 3.5 years. For the remainder of the time, since costs are already paid for, revenues would equal profit.

In the other extreme case, the garage would receive only enough revenue for their payback period to be exactly 8 years. An annuity of $427 would accomplish this. The rest of the annual revenue equals $2,583, creating a present value of $18,190. The vehicle owner would thus make profits of approximately $3,520 during the 8-year span.

However, a more realistic revenue sharing method would be to split revenues based on the portion of costs that each party takes on. Since the vehicle owner's battery-wear costs are approximately 5 times higher than the parking garage's infrastructure costs, this would create a revenue sharing scenario of 5:1, or 84% to 16%. This case splits the annual revenues into a payment of $2,528 for the vehicle owner and $482 for the parking garage. When these cash flows are discounted, the vehicle owner would make profits equivalent to an upfront payment of $3,070, and the garage owner would have a payback period of about 6.8 years. An upfront payment for an individual looking to participate in V2G would be ideal, as one of the biggest barriers to EV adoption is that they generally cost more to purchase than their conventional-vehicle counterparts due to battery costs (NRC, 2013). Thus, consumers often cite this upfront cost as a large reason for not buying an EV. A guaranteed payment before the V2G contract period would help solve this issue. For the garage, a payback period of 6.8 years is on the edge of being reasonable for a business. Payback periods are relative, though Miller (2013) states that payback periods in the realm of 5 years are considered viable for businesses.

EV Incentives

If the electric vehicle owner were to be paid upfront for the profits generated through V2G, the previous section found that this payment would be around $3,070. The next step is to determine how much this would incentivize an individual to purchase an electric vehicle. One option is to look at current incentives in place for electric vehicles in the United States. Comparing how these incentives are currently affecting EV purchases can give a better idea of how motivating this V2G profit might be to car buyers. Currently, incentives come from both the federal government, as well as many states. A federal income tax credit of $7,500 is available for most EVs today (US EPA, 2015). In

addition, California also offers a rebate of approximately $2,500 for EV purchases[7]. With an average EV cost of around $33,000 in 2015, this makes the true value of an EV around $23,000 for someone in California (Kelly Blue Book, 2015).

Some literature has focused on how incentives and changes in vehicle costs affect vehicle purchase rates. Sierzchula, Bakker, Maat, & van Wee (2014) used a regression model to understand the effect of EV rebates affects uptake speeds in 30 different countries. The study finds a linear relationship between rebates in U.S. dollars to percentage increase in EV fleet size. Each $1,000 increase in financial incentives caused a country's EV market share to increase by 0.06%, this study finds. Since $3,070 is roughly a 30% increase in the current EV financial incentive, this linear model would predict that this new incentive should raise demand for EVs 30% as well.

Other studies have used price elasticities of demand for traditional and electric vehicles to understand how changing the price of the vehicle might change demand. Lawrence (2015) and Glerum (2013) found price elasticities of demand of -1.6 and -2.0, respectively, which is relatively elastic. Given that $3,070 of financial incentive would represent a 13% decrease in price for the average EV in California, this means demand is expected to rise by 21-26%. This range in demand increase is fairly similar to the 30% prediction using the linear model, despite these studies using very different methods. An increase of demand of approximately 25% is a very significant rise for the EV market.

The California Air Resource Board (CARB) recently put together its own goals for the transition to electric vehicles through its Zero Emissions Vehicle Program. The initial stages of the program set a goal of 1.5 million electric/hybrid vehicles by 2025, an increase of almost 15 times the number of electric vehicles today in the state. The uptake speeds must increase in order to reach these goals, and V2G financial incentives show potential for helping California reach this goal.

[7] The precise amount is determined based on income bracket

Incentivizing EV uptake is also helpful for California to reach its larger goals of GHG reductions. Accounting for over 14 million gasoline-powered vehicles in California, transportation represents a large obstacle in California's move towards 1990 GHG levels. Vehicles account for well over half of the emissions that contribute to ozone and particulate matter and nearly 40 percent of the greenhouse gas emissions in California (California ARB, 2015). Thus, a transition away from gasoline-powered cars to electric vehicles is imperative to California's success in reaching its clean energy goals. A quick calculation shows that increasing demand for EVs by 25% could potentially replace 10,000 conventional gas vehicles in one year, reducing CO2 emissions by 47,500 metric tons (US EPA, 2015).

Market Size

While the profit calculations reveal that V2G is a feasible economic opportunity for vehicle owners and businesses, another test of feasibility is to calculate how many V2G equipped vehicles it would take to saturate the frequency regulation and overgeneration storage requirement. On one hand, if the market size for these services were too small, it would limit the number of potential V2G projects. On the other hand, if EVs were only able to provide a minute fraction of these total services, it would be worth considering whether this technology is worth pursuing from a macro perspective.

In 2009, the average size of all regulation services in California was 6,023 MW (Damato, 2011). Assuming that an EV would be limited by the 30 kW line, (as used in the profit calculations) this would mean about 207,000 EVs would saturate the regulation market. Considering there are about 100,000 EVs in California today, this number seems reasonable. There is still room for additional EVs to provide regulation services, yet in aggregate they could provide a significant portion of the total requirement.

Overgeneration is projected by CAISO to reach 15,300 MWh per year by 2024. EVs with 85 kWh batteries like the Model S would be able to saturate this market with a total of 180,000 vehicles. This number is similar to the saturation point of frequency regulation, and again seems reasonable enough for V2G to be a significant help.

Additional benefits of V2G

V2G also has a handful of non-monetary benefits that could stimulate further EV adoption and bring other societal benefits to California. Just behind the economic barrier, the lack of charging infrastructure is the second largest obstacle preventing many potential EV users from buying one (Nigro, 2015). EVs have limited ranges, and many drivers have uncertainty that chargers will be available when they need them to power their vehicles. V2G necessitates charging infrastructure for the vehicles to interact with the grid, and thus has the potential to catalyze the development of charging infrastructure. The prospect of V2G profits might also encourage parking garage owners to increase garage capacities and update charging infrastructure, making transportation easier for EV owners. All of this additional infrastructure could generate the confidence and certainty potential EV buyers need to purchase a vehicle.

Another interesting benefit of incentivizing V2G is that this could create a feedback cycle for additional EV uptake. As individuals begin learning about V2G and purchasing EVs, businesses will be more inclined to invest in V2G infrastructure – this, in turn, should create an even bigger market for V2G and encourage more individuals to invest in the technology. It may take time to set in motion the initial V2G projects, but once these businesses are underway it should create a positive feedback loop of additional EV and V2G adoption.

Finally, V2G vehicles could generate additional environmental benefits by replacing current generators. Many of the current resources that provide services like frequency regulation are heavy-polluting thermal generators (Parsons et al., 2013). If V2G becomes a more attractive and cost-effective way to provide these services, it could potentially help retire many of these older power plants.

Technological Considerations

Some considerations going forward are that many of the technical aspects of V2G have not been discussed in this study. V2G is heavily reliant on smart grid technology with access to all available information about the grid and vehicles. This technology must be further researched and developed in order for V2G to become a reality in California.

Smart grid technology is not only imperative for V2G, but will also benefit the continued integration of vehicles with the grid. As more people begin to adopt EVs, and vehicles become a larger load on the electrical system, it will become increasingly important to manage and balance the needs of vehicles and other grid users. Smart grid technology should be able to account for the different, yet compatible, needs of drivers and grid end-users by time-of-day, and even create automated grid management systems to most efficiently distribute electricity.

Conclusion

The V2G concept is exciting, and this study has shown the multi-faceted benefits that it can bring to California. The technology offers mutual benefits to the transportation and the electric power systems. The financial incentive to individuals could help transform the transportation sector from a vast array of carbon-emitting vehicles to large numbers of EVs. V2G also brings much-needed energy storage to the grid, which has the potential to help reduce the state's dependency on fossil fuels. This study was one of the first to put forward a business plan with quantified benefits for parking structures and individuals, and presents results that look attractive for both parties.

This study is not perfect. The work presented here dealt with significant uncertainties in key area affecting the viability of V2G, including the current accuracy of upfront costs of V2G infrastructure, precise usage patterns of vehicle owners, their willingness to leave cars in garages for significant period of time, and the accuracy of forecasts of battery costs and capacities. As a result, the assumptions within the economic models presented here are conservative to reflect this uncertainty, and the benefits of V2G are likely to increase with greater understanding of these factors.

Public education is one of the most important steps in order for V2G to become a reality. V2G is currently a largely theoretical subject, with very few people knowledgeable about its fundamentals and benefits. One entity that should become responsible for helping to educate the public is car manufacturers. Companies such as

Nissan or Tesla, who could benefit from selling more EVs through increased knowledge about V2G, should convince the public that this technology is beneficial.

Finally, as with other new technologies, there is a legislative need. Legislation that encourages V2G and potentially subsidizes chargers or other infrastructure could complement any technological innovation or marketing. If California begins to understand how much V2G could benefit the grid, they could become more interested in passing policies to incentivize V2G. Ultimately, people implement and execute disruptive technological advancements, and more often those with a willingness to "make a leap of faith" and apply entrepreneurial skills to explore new areas of business. California is a logical place for the V2G revolution to begin, both for the economics of its energy and environmental goals, and for the enterprising spirit that flourishes in the Golden State.

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Appendix

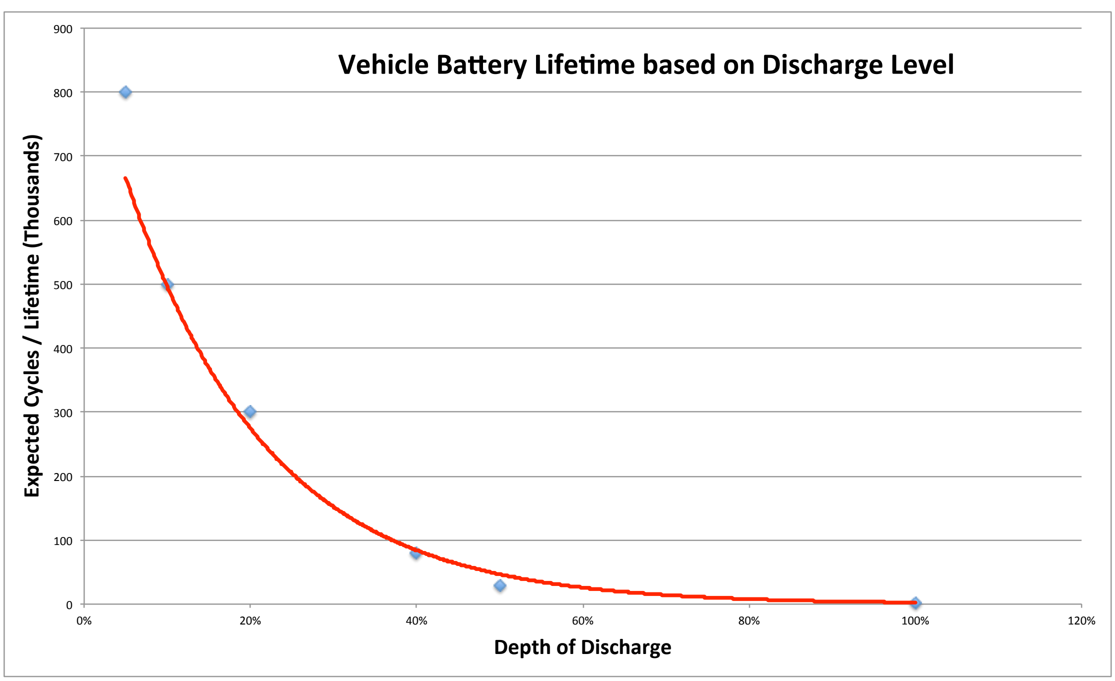

Figure 10: Vehicle Battery Lifetime based on Discharge Level

KEY
Low / High

	Model S		Leaf	
	Frequency Regulation	Overgen Storage	Frequency Regulation	Overgen Storage
Charge cycles/year	564,000	-	564,000	-
Δ SOC	1.0%	-	3.0%	-
Battery lifetime (years)	5	-	1.8	-
Revenue/Year ($)	2850 / 4150	160	2850 / 4150	160
PV[Battery Costs] ($)	7432 / 14673		10114 / 20425	
Infrastructure Cost ($/unit)	1000 / 3000	1000 / 3000	1000 / 3000	1000 / 3000
Total Costs ($)	8432 / 17673	-	11114 / 23425	

Figure 11: Intermediate Calculations Scenario 4

KEY
Low / High

	Model S		Leaf	
	Workday Shift Only	Workday + Nighttime	Workday Shift Only	Workday + Nighttime
Charge cycles/year	240,000	600,000	240,000	600,000
Δ SOC	1.0%	1.0%	3.0%	3.0%
Battery lifetime (years)	12.5	5	4.2	1.67
Revenue/Year ($)	1398 / 2396	2940 / 4290	1398 / 2396	2940 / 4290
PV[Battery Costs] ($)	3975 / 7950	7826.5 / 16653	4527 / 9055	11317.5 / 22635
Infrastructure Cost ($/unit)	1000 / 3000	1000 / 3000	1000 / 3000	1000 / 3000
Total Costs ($)	4975 / 10950	8826.5 / 19653	5527 / 1255	12317.5 / 25635

Figure 12: Intermediate Calculations Scenarios 1 & 2

CAISO Monthly Renewable Generation Curtailment Frequency by Hour of Day, Month									
		Hour of Day							
		9	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Month	***1***			1	4	4	5	1	
	2		1	3	7	9	6	2	1
	3	8	14	22	24	24	23	17	7
	4	16	29	29	29	29	29	24	13
	5	18	23	27	28	26	22	13	5
	6	10	16	21	21	20	17	5	2
	7	4	4	4	3	3	2		
	8			2	2	1			
	9	1	4	7	9	8	4	2	1
	10	2	4	4	7	6	5	4	1
	11		4	7	12	12	6	1	
	12			3	5	7	4	1	

Figure 13: Renewable Overgeneration Frequencies