

Vehical to Grid Bi-Directional Charging

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ABSTRACT

California's low-carbon transportation targets depend on the use of plug-in electric vehicles, but the high cost of these vehicles continues to be a hurdle. Technologies that connect vehicles to the grid may offer both financial advantages and chances for system stabilisation. In order to investigate revenue generating, the U.S. Department of Defence held a demonstration at Los Angeles Air Force Base. Reusing battery packs can save ownership costs over time, minimizing environmental effects and battery replacement expenses. In order to support clients who are prepared to donate their assets for vehicle-to-grid applications with compensation schemes, this study measures battery life and performance for both present and future vehicle-to-grid use in California.

Introduction

In recent years, there has been a huge interest in the industry as well as from consumers towards making a shift from gasoline-run cars to electric cars. There are several reasons behind this interest. Some of these are heightened awareness regarding global warming,¹ decreasing fossil fuel reserves,² and the craze of minimizing one's carbon footprint. Motivated by the growing market demand, scientists across the globe are working tirelessly towards developing improved batteries that have high energy densities, capacities, and long cycle lives. While work on developing improved batteries and more efficient electric cars is advancing steadily, there is another related idea that has been in the limelight recently.

Known by the term, *Vehicle-to-Grid (V2G)* technology, the concept involves parked vehicles generating electricity for the grid.⁴ At first encounter, one might speculate whether this concept can be useful at all and even if it is indeed useful, how effectively this can be implemented. An important statistic that motivated this concept is that in the United States, a typical car is on the road only for about 5 % of the day.^{5,6} Analyses indicate that even during peak traffic hours, as much as 90% of the cars remain parked.⁵ In addition, an equal

percentage of the cars are not driven for even half of their full driving range every day. Thus, each parked vehicle can be considered as an under-utilized source of energy, and may even be shown to possess negative value because of the parking costs.⁷

To determine whether V2G is feasible, it is important to perform a cost-revenue analysis, taking into account the projected number of vehicles that will take part in V2G power, the total available storage capacity in the vehicles, and the power requirements of the grid supply. Research on merits of this technology implementation

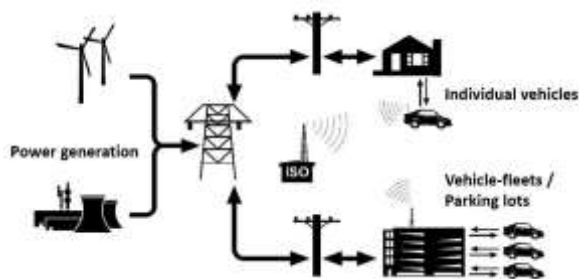


FIG. 1: A schematic illustrating a model implementation of vehicle-to-grid technology.³ started back in 1997,⁸ when commercial electric vehicles on the road were absolutely minimal. So, as we currently envision a world with widespread use of electric vehicles, it becomes compelling to compare the power capabilities of the total vehicle fleet and the grid.

This paper discusses the feasibility of V2G concept using economic analyses, projected demands and technological improvements.

Electric-Drive Vehicle (EDV) fleet - an overview

Three features are deemed important for a V2G enabled vehicle:

1. power supply to the grid
2. communication systems for the grid to access the vehicle's power
3. a high precision measurement system to track the power flow³

In addition to devising these guidelines, Kempton and Tomic also illustrated a scheme for V2G transmission

as shown in Figure 1.³ In the schematic, a one-way flow of electricity is represented by a single-headed arrow, whereas a two-way flow is represented by a double-headed arrow. The electricity flows one-way from the generators to the grid, but flows both ways from the vehicles to the grid. The Independent System Operator (ISO) sends requests that reach the vehicles (that have opted to receive the requests) directly, through a mobile network, or an internet connection.³ The ISO may also choose to contact the fleet operators that control a parking lot with a considerable number of parked cars, which provide power back to the grid.

In the United States, there are about 240 million light vehicles (passenger cars, vans, and light trucks).⁹ Although all these vehicles have batteries within them, V2G power is proposing to make use of the power only from electric-drive vehicles (EDVs) vehicles that use an electric motor to drive the wheels. Based on the source of the vehicle's electricity, EDVs can be classified into three types,³ namely (i) Battery EDVs, (ii) Fuel Cell EDVs, and (iii) Hybrid EDVs. All three types of vehicles generally feature power electronics with sinusoidal AC with varying frequencies. This renders the electricity output of the EDVs to be grid-ready.

Battery EDVs

Battery cars retain electricity from the grid in electrochemical cells. Lead-acid batteries were the least expensive option, but now nickel metal-hydride (NiMH), lithium-ion, and lithium-metal polymer batteries seem to be more cost-competitive with their long lives of cycles, compact size, and light weight. To power the batteries, they need to be connected to the grid. Since this connection suffices to provide energy back to the grid, the capital costs for rendering a battery EDV to be V2G compatible, would be very minimal.³

Fuel Cell EDVs

Energy is stored as molecular hydrogen. Fuel cells produce electricity by taking in the hydrogen, along with oxygen, while water is released as a byproduct. The electricity produced, must be converted onboard into 60 Hz AC. So, since the power electronics does not already come along with the fuel-cell vehicle, the cost of the required grid connection has to be tolerated by the consumer.³ This is typically referred to as a V2G *capital cost*, in the analyses.

Hybrid EDVs

Hybrid EDVs run on a combination of an internal combustion engine and a generator attached to a small battery. Hybrid vehicles operate more efficiently than the traditional gasoline-powered vehicles. This is because the fuel usage is reduced by working the electric motor during slow traffic, and recapturing the kinetic energy that is usually lost during braking. Hybrid vehicles have been successfully commercialized, as evident from the market statistics of the Toyota Prius, the Honda Insight, and the Civic Hybrid models.³ Plug-in HEVs (PHEVs) fall in the same category, but differ by using a larger battery and a plug-in charger. The larger battery enables them to solely run on electric power for 20 to 60 miles.

A typical full-sized EDV is capable of producing a power of 50-100 kW, but for the purposes of harvesting the power as EDV, only about 15-20 kW is considered due to limitations on the wiring.³

Power Markets

In the United States, there are about 9000 electric utility generators with a total power capacity of 1110 GW, as of 2014. All these utility generators will be controlled in real-time by an Independent System Operator. Although V2G power may be considered to be available for the entire grid, the cost of V2G power may not be favorable for all consumers. It is important to analyze the nature of each consumer-sector, and market the V2G power accordingly. The electricity market can be widely classified into four categories, based on its control regime and the customers it serves.³

Baseload Power

This is the power that is provided round-the-clock to all the users, both residential and industrial. Since it is important to maintain a steady production at a low cost-per-kWh price, this is typically sold in long-term contracts. Baseload power is generated cheaply by the use of nuclear and coal generating stations.³ Nevertheless, its availability is restrained by some qualities like small storage capacity for energy, limited life for the equipment, and relatively high cost per kWh. Much more significant than that is that the load and cost exclude the V2G power from eligibility for this sector..

Peak Power

This market category is used to describe the power that is generated and supplied when demand for consumption is high and high. Short-term power generating plants, typically supply the peak power requirements. Demand tends to be for only a few hundred hours yearly. Because of the inherent storage limitations of the V2G power, it is not always possible to harvest it for serving peak demands. V2G power would turn out to be useful only if an entire fleet of vehicles is available for the use of the grid.

Spinning Reserves

The generation power that is available within a short period upon a request from the grid operator, is usually termed as a spinning reserve.^{3,4} The response time is usually within a few minutes. A unique characteristic of spinning reserves is that its market value does not lie on the amount of energy consumed, but for the time the power is available. This means that even if the energy or the power listed in the contract has not been utilized or drawn completely, the payment would be done towards the amount of time the generator was available for the intended utility. This type of contract appears favorable for V2G power since, the EDV owners will benefit just for keeping them connected to the grid. Moreover, these contracts specify limits for the number of calls per year, and duration of each call from the grid. This would enable more flexibility to the V2G owners. Typically, the number would not exceed 20 calls per year, with a maximum of 1 hour per call.³

Power Capacity of V2G

Before determining how much power a V2G vehicle can provide, it is important to list out the limitations of V2G power. Firstly, the V2G power is limited by the amount of energy that can be stored in the vehicle, and the maximum power capability of the vehicle's power electronics.³ Then, it is also limited by the current carrying capacity of the wires connecting the vehicles through the building. For a typical electric vehicle, the circuits have a power capacity usually above 100 kW, whereas a home's maximum power capacity would be between 20-50 kW. The building-wiring maximum can be calculated as follows. With a home wiring at 240 V AC, and a typical 50 A circuit rating, one can calculate

a line capacity maximum of 12 kW. For a commercial building, the limit could be about 25 kW or higher.³

A mathematical formulation has been developed for calculating the limitation of the onboard energy storage.³

This is given by:

$$P_{vehicle} = \frac{(E_s - \frac{d_d + d_{rb}}{\eta_{vehicle}}) \eta_{inv}}{t_{dis}}$$

Where $P_{vehicle}$ denotes the maximum power from V2G in kW, E_s denotes the stored energy available as DC, d_d denotes the distance driven in miles with full storage, d_{rb} denotes the range buffer distance specified by the driver as minimum reserve required for an unanticipated commute/trip, $\eta_{vehicle}$ denotes the vehicle driving efficiency in miles per kWh, η_{inv} denotes the electrical conversion efficiency of DC to AC, and t_{dis} denotes the time the vehicle's stored energy is dispatched in hours

A case study with reasonable assumptions

Using the aforementioned formulation, a sample calculation was performed to estimate the power output of a typical electrical vehicle, the Toyota RAV4,³ for instance. The value of d_d would depend on the driving pattern, type of vehicle, and the vehicle owner's strategy for selling power. On an average, the average daily miles driven by a commuter in the US is about 32 miles.³ It is reasonable to assume that the power equivalent of about half of this distance would be available as V2G power. Some surveys point out that drivers prefer to maintain a minimum range buffer, r_{db} of 20 miles. Time dispatched, for peak power would range for 3-4 hours, and be lower for other markets. Even for long, repeated regulation services, the time dispatched might not exceed 20 minutes per day.

The battery of a Toyota RAV4 electric vehicle is 27.4 kWh. However, being a Ni-MH battery, it should not be discharged below 80% depth of discharge, and so, it is assumed that about 6 kWh would be available for V2G power. The rated vehicle efficiency is 2.5 mile/kWh, and an inverter efficiency of 0.93 is assumed. Using the formulation, it is estimated that a RAV4 vehicle would provide about 42 kW of regulation power.³

Revenue vs. Cost Analysis for V2G enabled vehicles

A detailed cost-revenue analysis was performed based on the electric vehicle market, and the power costs in the year 2005,³ by Kempton and Tomic. In short, about 15 kW power is assumed to be available from a vehicle towards use by the grid. With CAISO's market price of \$0.04/kWh, and a retail electricity price of \$0.10/kWh (Rates used for sale from a battery vehicle), and assuming that the vehicle remains connected to the power grid for 18 hours a day, a revenue of \$4928 is expected per year for the vehicle owner.³ It is interesting to note that when only a 10kW power was considered available, the revenue came down to \$1500/year/vehicle. This means that the EV owners would gain more by spending initially on the expensive wiring required for 15 kW power, so that they could get 3 times more revenue within a single year. If a home requires a wiring upgrade to be V2Gready, it is assumed to cost \$1500 for a set-up capable of handling 15 kW.³ The round-trip efficiency (grid-battery-grid) is assumed to be 73%. Considering these factors, one would expect a net revenue of approximately \$2500 in the first year.³ One must note that these estimates were arrived at, by making modest estimates of available power on the vehicle. With the development of high capacity EVs (Tesla, with a 85 kWh battery pack,¹² for instance) in the last decade, one could expect to generate more revenue, and also take into account some unanticipated events during the year.

Suitable Economies and Jurisdictions for V2G Implementation

Given the nature and characteristics of V2G power, certain geographical regions and jurisdictions are expected to have a greater interest towards V2G implementation, and thus, would favor the market development.⁴ For instance, V2G power would suit the needs of governments that desire electric grid improvements, and high degrees of stability and reliability of frequency, but are reluctant to construct new power plants and transmission lines.⁴ This would also be appealing to nations where competitive markets exist for regulation and spinning reserves. In these regions, the costs for these services would be considerably high. Geographic regions which face transmission constraints (say, a peninsula, or a gridisolated island) would also be interested in taking up

V2G power implementation.⁴ In addition to all these technical factors, certain administrative reasons might also play a role towards V2G implementation. For example, this concept might interest a government whose policies are inclined towards development of new industries, technologies or employment, thereby creating opportunities for more local jobs.⁴ The V2G concept might also suit governments that have a coordinated control over transportation and electricity, thus providing administrative convenience.

Nations which have committed to renewable energy resources, with wind resources in particular, might also want to implement V2G and provide more storage space for surplus wind power.⁴ In addition, geographic areas that have large automobile fleets next to the wind resources would also show interest in its implementation. This would try to get rid of the limitation that wind power transmission faces, while serving distant and populous cities.⁴ Some examples of these areas include the east coast of the US, UK, and the western states of Europe.

Prototypes Developed

Several prototypes have been kick-started around the world to test and demonstrate the advantages of V2G power. One such initiative is being undertaken by Edison International in collaboration with the US Department of Defense, by implementing a pilot project in California, employing the vehicle fleet at the Los Angeles Air Force Base.¹³⁻¹⁷ It is the first federal facility to replace all its general purpose fleet with PHEVs. A fleet of 42 PHEVs were made V2G compatible using an equal number of charging stations. The fleet was able to provide 700 kW of power, an amount that satisfies the power needs of 140 American homes on a typical summer afternoon.¹⁴ In addition, the fleet was also able to demonstrate that it enables the installation facility to earn revenue by enhancing the power reliability and stability of the grid.

More recently, in the summer of 2016, the automobile manufacturer, Nissan, and a multinational power corporation, Enel, launched a V2G trial in the UK.¹⁸ It consists of 100 Nissan electric vehicles (Nissan Leaf cars, and e-NV200 vans), whose owners would be able to sell the stored energy back into the grid. The company ultimately envisions to bring in all of its 180,000 Nissan electric vehicles into a V2G network, to generate a combined output of about 180 MW.

					
Range Description	PEV	PHEV	REEV	PHEV	PEV
	electric range: 75 miles fuel efficiency: 99 MPGe	electric range: 34 miles fuel efficiency: 46 MPGe	electric range: 31 miles fuel efficiency: 38 MPGe	electric range: 42 miles fuel efficiency: 43 MPGe	electric range: 100 miles fuel efficiency: 33 MPGe
General Payload Floor Size	22.8 cubic feet (range capacity) 3 seats	100 to 200 lbs payload 2 seat standard cab 8 seats crew cab	1000 lbs payload (range cab only) 2 seat range 12 seat passenger	1000 lbs payload 3 seats	170 cubic feet (range capacity) 22 passengers + driver
Battery Capacity	36 kWh	27 kWh	21 kWh	64 kWh	100 kWh

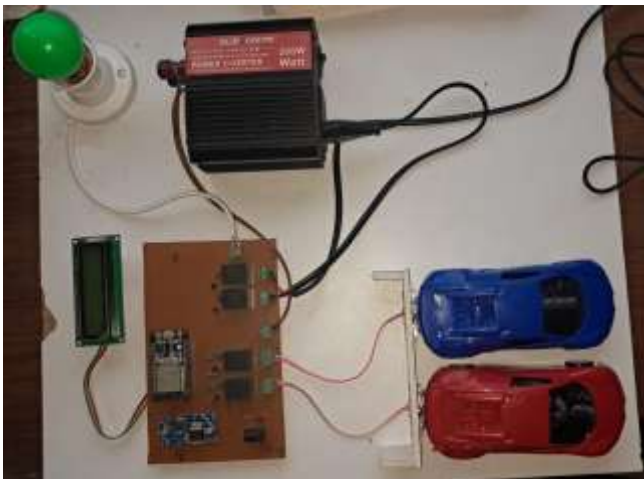


FIG. 2: Prototypes: (clockwise from top)

List of different types of EVs used in V2G pilot project at the Los Angeles Air Force Base,¹⁵ a BMW i3 at the demonstration of a demand-reduction trial,¹⁹ and a Nissan Leaf with the V2G connection set-up.²⁰

Apart from these active prototypes that are intended to directly test the feasibility of V2G, some companies have started to test certain individual components from the concept. For example, BMW implemented a demand-reduction trial,¹⁹ where its prime motive was to see whether it can communicate with multiple cars, and test whether it can control the number of cars that charge from the grid. BMW brought in 100 of its i3 car-owners from San Francisco area, and enabled communication systems on the car, so that BMW can signal the car to stop charging whenever there is a surge in the demand. For doing so, the utility pays BMW, which in turn incentivizes the car-owners.¹⁹

Obstacles ahead for V2G

Social and Cultural

Apart from the technological hurdles that face V2G, there are a couple of social and cultural barriers that exist to be resolved, before widespread implementation could be realized.¹¹ How consumers assess the savings is an important factor that determine the commercial

successes of new technologies. As evident from the nature of consumer acceptance of other previous technologies, it may turn out that even with technical issues resolved, consumer acceptance may not be as good as one expects. For instance, a significant problem is the “firstcost” that confronts the PHEV market, and serves as an economic disincentive.¹¹ On an average, a HEV costs \$4000 more than a conventional vehicle. For a typical vehicle that is driven for 15,000 miles/year at a gasoline price of \$2.50/gal, the payback period would be a minimum of seven years.¹¹ Thus, with the average ownership of just six years for an American car, this fact would not sound appealing to consumers. Surveys find that the buyers expect the fuel efficiency improvements to pay off for themselves within the first three years.²⁰ In general, it would take at least 10 years for conventional vehicles, and four years for a HEV.^{20,21}

The high oil prices in 2008 urged some consumers to shift from gasoline-powered vehicles to energy efficient all-electric ones. This can be seen as a simple reaction notwithstanding the high fuel price. It has been found that most of the consumers do not perform any detailed calculations to determine a car’s economic advantages before they buy it.¹¹

It is also important to note that the fuel efficiency improvements of a HEV can be realized only if the owners drive conservatively, and draw on vehicle’s regenerative braking. However, most drivers intuitively desire for high top speeds, aggressive acceleration, and less coasting, which reduce the fuel economy.¹¹ The compromises that a EDV owner has to make in this regard to achieve the preset fuel efficiency or payback, also serves as a potential limitation for the consumer acceptance of HEVs and PHEVs. Apart from these rational concerns such as cost, and range of the PHEVs, product styling and values, also play a significant role.¹¹ Some customers of HEVs believe that they can gain a better social standing through the choice of an environment-friendly vehicle.¹¹

Business and Industrial Factors

For this technology to realize widespread implementation, it requires policy makers, utility companies, and automobile manufacturers to come together and install vast amounts of infrastructure. The controllers of the existing infrastructure might try to impede the infrastructure developments necessary for a transition from internal combustion engine (ICE) vehicles into PHEVs. A similar behavior was observed

in the 1990's where traditional automobile manufacturers alleged that EVs do not provide any environmental benefits. They argued that EVs would have only a net negative impact on the environment, due to the lead emission from the battery production plants. Additionally, going electric would imply that the industry must create a whole new group of suppliers, technicians, and assembly procedures. This is because of the stark difference in the nature of engines in ICE vehicles and electric vehicles. ICE vehicles use numerous components and moving parts that require precise engineering for functioning at high temperatures.¹¹ On the other hand, electric vehicles require just one major moving part, and a controller. Naturally, there would be a resistance towards this transition that leaves about a million automobile-technician jobs at stake.²²

Although it appears as though V2G technology implementation might affect a battery's lifespan due to repeated cycling, a study claims that the benefits and the value-to-utility of the V2G technology exceeds the costs arising due to reduced battery life.⁸ It is also interesting to note that this study arrived at this conclusion even after making unfavorable assumptions about the cost and lifetime of a typical battery.

Since V2G has the potential of decreasing profitability uncertainty associated with electric vehicles, V2G may also encourage governments to provide subsidies for utility companies and electric vehicle industries to develop, widen and maintain their vehicle charging infrastructure.^{23,24} Utility companies like ComEd have already started their research on framing V2G policies.²⁵ PJM in collaboration with University of Delaware, recently published their test results on the usage of V2G power for regulation services.²⁶

Conclusion

To summarize, V2G is a potential technology that may accelerate the transition towards EDVs by improving the commercial viability of the electric vehicles.⁸ Time critical services like regulation and spinning reserves can be served by tapping just 3% of the electric vehicles' fleet.^{4,27,28} In the long-run, we could envision using about one-fourth to half of the electric vehicle fleet, to serve as back-up generation and storage for renewable energy.⁴ The fact that there is practically no stakeholder in this ecosystem (consisting of vehicle manufacturer,

vehicle owner, Independent System Operator, and the end-user of V2G power) who is at a loss, provides a compelling reason for us to move towards this technology, and drive power grids and electric vehicles towards a V2G-compatible environment.^{4,29} This zero-loss claim could be confirmed by implementing V2G on a smallscale, perhaps on micro-grids, where its reliability and the cost-power analysis could be studied in detail.³⁰

We must recall that the concept can be deemed viable only if it can provide electricity comparable to the existing sources of generation. From the technical discussions in the paper, it is quite clear that V2G power cannot be used for bulk generation and storage, owing to certain fundamental engineering characteristics of V2G power, and the evaluation of its cost per unit of power.³ But the main playground for V2G would be where there is a price for electricity just being always available on request, and an added energy price for the power actually supplied.^{3,4} The highest value ancillary service is regulation with an average value of \$30-\$45/MW per hour. In addition, parked V2G-enabled vehicles can be used as dispersed energy storage media for intermittent, renewable energy resources like wind and solar.⁴

Despite all these merits of V2G technology, the research community still acknowledges that the transition from internal combustion engine vehicles to Electric Drive Vehicles (EDV) may take many more years to achieve, and is limited by the technological and infrastructural developments necessary for communication between the vehicles and the grid.⁶ Research efforts must also continue to improve the life expectancy of batteries used in an average electric vehicle.³¹ Automobile manufacturers and the vehicle owners would need convincing evidence that frequent bidirectional transfer of V2G power would not deteriorate the battery's cycling capacity.^{6,32} Regulations dealing with the role of independent system operators (ISO) and the vehicle owners are still evolving, and can be put to test only with certain pilot projects similar to the one that kicked off in California.^{13-17,33} These are some of the technological obstacles that face V2G.

In addition to the technological challenges, certain social, cultural, political and economic causes also remain to be addressed, before we could truly realize the impact of this technology.⁶ Consumer acceptance and their enthusiasm in this nascent concept is something that cannot be predicted for certain. While battery

powered vehicles have been projected to be a green technology for over a decade, only recently have people started showing their interests towards EV market. With that in mind, it would be safe to assume that it would require even more time, efforts and convincing evidence to popularize V2G technology.

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