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Using vehicle-to-grid technology for frequency regulation and peak-load reduction

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ABSTRACT

This paper explores the potential financial return for using plug-in hybrid electric vehicles as a grid resource. While there is little financial incentive for individuals when the vehicle-to-grid (V2G) service is used exclusively for peak reduction, there is a significant potential for financial return when the V2G service is used for frequency regulation. We propose that these two uses for V2G technology are not mutually exclusive, and that there could exist a “dual-use” program that utilizes V2G for multiple uses simultaneously. In our proposition, V2G could be used for regulation on a daily basis to ensure profits, and be used for peak reduction on days with high electricity demand and poor ambient air quality in order to reap the greatest environmental benefits. The profits for the individual in this type of dual-use program are close to or even higher than the profits experienced in either of the single-use programs. More importantly, we argue that the external benefits of this type of program are much greater as well. At higher V2G participation rates, our analysis shows that the market for regulation capacity could become saturated by V2G-based regulation providers. At the same time, there is plenty of potential for widespread use of V2G technology, especially if the demand for regulation, reserves, and storage grows as more intermittent renewable resources are being incorporated into the power systems.

1. Impacts of peak energy demand

Electricity demand can dramatically increase on hot summer days when the use of industrial and commercial air conditioning becomes prevalent, resulting in what are known as High Electric Demand Days (HEDDs). These periods of high power usage (peak load) often require the use of “peaking” electric generation units to meet demand, yielding a host of environmental and economic consequences.

The cost of electricity use can increase considerably during periods of peak loading. In a 2006 examination of the PJM (Pennsylvania, New Jersey, and Maryland) market, it was found that a 1% shift in peak demand could result in cost savings of 3.9%, representing billions of dollars at the system level [1]. The growth of peak demand, and the subsequent economic result on electricity consumers, is thus of considerable importance to future grid planning and management. Across the nation, peak demand has grown almost 70% in the past 20 years. The increase in overall electricity demand has heightened the necessity of additional generation facilities, but the reality of extensive peak demand growth has resulted in increased focus in introducing new peaking power plants when considering the installation of new generation capacity [2].

Peaking plants by definition operate only rarely, however, and are therefore not financially viable if their generated electricity is sold at wholesale market value. As such facilities are necessary to ensure system reliability standards, plant income must be supplemented by some factor in order to ensure that capital costs are covered. In deregulated markets, this issue can be handled by allowing generating facilities to participate in an Installed Capacity Market (ICAP) [3]. The capacity market structure pays a plant for its ability to generate electricity and meet demand, as a supplement to the profit earned from actual sales of electricity. This capacity payment can be significant, and is the primary means of covering capital costs for peaking plants [3]. This market is expected to generate reasonable incentive for market suppliers to invest in new generation units as needed.

Examining the energy market in New York State, however, indicates that such a market may not necessarily result in the desired outcome of encouraging new generation facilities. The New York State capacity market in 2005 and 2006 generated $1 billion/year, more than enough to cover the annual capital costs of new peaking plants [3], yet merchant generators have been reluctant to actually build new generation facilities. In 2006, when the New York Power Authority was faced with a potential system reliability crisis by 2008, they resorted to *ad hoc* measures to ensure the reliability of the system, delaying the retirement of several older plants and

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treating a cross-sound transmission link as firm capacity [3]. Many of the generating facilities whose operational lives were extended are old peaking plants in New York City and Long Island with relatively high endemic costs. Thus, the market has resulted in an extension of the lives of some of the most cost-inefficient peaking plants.

While peaking plants often only operate for a few hours during HEDDs, these generators can be among the dirtiest plants in a region [2]. They can contribute significantly to the total amount of nitrogen oxides (NO_x) emissions from electricity generation, which is a chemical precursor to the formation of ozone. Ground level ozone can have aggravating effects on existing respiratory conditions and can negatively affect even healthy adults and children when present in sufficient quantities [4]. Ground level ozone and nitrogen dioxides are both criteria pollutants in the National Ambient Air Quality Standards (NAAQS). Ozone present in more than 72 ppb for an 8 h window results in a region being a non-attainment area for NAAQS. Peaking plants are generally used on the hottest days of summer, in conditions most suited to ozone formation. Average daily NO_x emissions can as much as double on peak demand days, representing a significant potential for non-attainment of NAAQS in a given region [2].

Due to the regional and local environmental costs of using peaking plants to meet electricity demand, it is important to reduce the need to rely on these plants for power generation. Currently, the main peak-load reduction strategy is demand response. Significant economic and environmental benefits can be reaped by this “smoothing” of the demand curve, identifying demand response as a key component in managing a modern energy infrastructure. However, more peak-load reduction strategies are needed.

2. PHEVs and vehicle-to-grid technology (V2G)

Plug-in hybrid electric vehicles (PHEVs) are the next stage of evolution for today’s hybrid car models. PHEV technology expands on the current generation of hybrid vehicles by allowing the vehicle to charge its battery while stationary using the electricity grid. A PHEV can be operated using only the electric motor for several miles, so that the combustion engine does not even turn on for short trips. Widespread PHEV use will have substantial effects on fuel and electricity use, offering potential for increased oil independence as well as decreased emissions.

PHEVs may further increase the efficiency of electric generators and reduce overall emissions by providing two vehicle-to-grid (V2G) services: energy storage and ancillary services. As energy storage devices, PHEV batteries may be charged when the cost of generating electricity is low and discharged when it is high, decreasing the use of low-efficiency, high-emission peaking units. Ancillary service is a more broad term, which can refer to services provided to the electric grid such as frequency regulation or electricity reserves. While there is certainly potential for V2G technology to be used as reserves (spinning reserves in particular), the focus of this paper is on frequency regulation, which refers to the adjustments to electricity supply (both up and down) that power system operators must make in order to balance electricity supply and demand in real-time. In this paper, we analyze the economic feasibility of using an aggregated V2G service as grid-scale energy storage for peak reduction and as a frequency regulation provider.

There has been previous research in each of these areas. Several recent studies have shown that there is potential for significant economic return for using V2G as a frequency regulation provider [5–7]. Additionally, another recent paper shows that there is very little return for PHEV owners if they were to use V2G exclusively for peak load reduction [8]. The goal of this paper, however, is not to show the economic feasibility of these two uses for V2G separately, but to show that these two technologies are not mutually exclusive. We propose that while V2G technology can be used for frequency regulation on a daily basis, it can also be used for peak load reduction during times of extremely high electricity demand and poor ambient air quality. This framework ensures that drivers experience sufficient economic return for their participation in the V2G service, and simultaneously provides environmental benefits during the times in which it is needed most. Additionally, we show that it is possible that this dual-use V2G service could actually provide higher profits to the participants than either of the single-use V2G services on their own.

In order to get to the analysis of the dual-use V2G service that we propose here, we first look at V2G for peak reduction and V2G for frequency regulation separately. For the analyses that follow, we require a set of general assumptions, which are described below. Firstly, we assume that all of the V2G participants are aggregated into a single controllable power resource as described by Quinn et al. [6]. Though we do recognize that it would be necessary for the aggregator to earn some percentage of the profits, we do not make any specific assumptions about the amount of profits they would earn; instead, we present the total profits that would accrue to the individual before any percentage of that is taken by the aggregator. Furthermore, we use the specifications of the upcoming Chevrolet Volt as a basis for our analysis. The Volt has a 16 kWh lithium-ion battery that uses a 50% depth-of-discharge; meaning only 8 kWh of the energy on the battery is available for both driving and any V2G use. The 8 kWh of the battery charges fully in approximately 6 h, which implies an approximately 1.33 kW charge rate, given that we assume that the charge rate is constant. The full-electric range of the vehicle is 40 miles, meaning the vehicle can drive 5 miles per kWh [9]. Finally, we assume for the economic analysis that the aggregated V2G service is a price taker, having no significant effect electricity loads or prices. For the purposes of this analysis, this assumption is essentially the same as assuming there is a very low rate of participation in the V2G program. This assumption will be relaxed later (in Section 6), when we discuss the impacts of possible high participation scenarios.

3. V2G for peak reduction

Calculating the amount of peak load that can be reduced through V2G, as well as calculating the profits available to the individual requires specifying the amount of energy that each vehicle will be able to sell to the grid. Using data from the National Household Transportation Survey [10], we determine the average number of miles driven by New York residents per day, and then determine the percentage of individuals who fit into each of five groups depending on the average number of miles driven per day. We assume that every member of each of these groups drives the average number of miles traveled in that group, and that any electricity not spent on driving is available for V2G. The percentages of individuals that exist in each of these groups as well as the available electricity left on the vehicles in each of these groups are shown in Table 1.

Table 1
Description of driver groups for New York residents.

Driver group	Percentage of drivers within each range	Average number of miles	Available kWh per vehicle
0–10 miles	22.18%	4.38	7.124
10–20 miles	20.31%	14.84	5.031
20–30 miles	20.71%	25.33	2.934
30–40 miles	13.95%	33.61	1.278
40+ miles	22.86%	59.39	0

The groups of drivers presented in Table 1 will be referred to several times throughout the paper, as we calculate the potential profits for the drivers in each of these groups. We will see that those individuals who are part of the higher mileage groups, and thus have the least spare energy to sell to the grid, will receive the least profits. The one exception to this is the group of drivers who average more than 40 miles per day and thus are not able to participate in a V2G program. In 2006, the New York City Department of Transportation estimated that there are approximately 1,130,002 vehicle commuters into New York City on a daily basis [11]. Using this figure, and those presented in Table 1, we can estimate the potential that V2G has for reducing peak electricity load in New York City. We find that with 1% of commuters participating in the program, there is about 38.28 MWh of available power. The relationship between participation rate and the amount of power available is assumed to be linear, such that at a 10% participation rate there is approximately 382.8 MWh of available power, and so on.

For most of the remainder of the analysis we will assume a low participation rate, so that there is no effect of changes in electricity load on prices. The implications that result from high participation scenarios will be discussed in Section 6. To describe the potential profits for participating in a V2G program that is solely used for peak reduction, we refer to Eq. (1):

$$\Pi = R_{en} + R_c - (C_f + C_{en} + C_d), \tag{1}$$

where Π is the total annual profits from V2G participation; R_{en} is the total annual revenue gained from the energy market; R_c is the total annual revenue gained from the capacity market; C_f is the annualized fixed cost of upgrading a vehicle to V2G-capability; C_{en} is the annual cost of purchasing energy that will be sold back to the grid; C_d is the annual cost of battery degradation.

Note that we calculate each of these costs and revenues as they apply to the amount of electricity sold to the grid by each vehicle as described in Table 1, and we present the results of Eq. (1) for each of these groups in Table 6. Referring back to Eq. (1), R_{en} and C_{en} can be viewed in tandem, as they are calculated in a similar manner. We use hour-ahead Locational-Based Marginal Pricing (LBMP) data from the New York ISO for the New York City region in the years of 2007, 2008, and 2009 to come up with our estimates [12]. In the calculations of R_{en}, we make the assumption that electricity will be discharged while people are at work, since these are the hours that generally experience the highest electricity loads and prices. To calculate R_{en}, we multiply the maximum electricity price for each work day by the amount of electricity that is available to be sold to the grid, and then sum up over the year. To determine C_{en}, we assume that vehicles are being charged during the 6 h of the night that generally have the lowest electricity prices (12 a.m. through 5 a.m.). The average price over these 6 h is defined as the charging price for each day. Thus, the annual cost of energy is the amount of spare electricity on each vehicle multiplied by the charging price at each day, and then summed over the year.

In this analysis, we are assuming that the aggregated V2G service is essentially being compensated as if it were a power generator. Because of this, the V2G participants should be eligible for a capacity payment just as power generators are. Most peaking power plants only supply energy during the days and hours of the year with the very highest electricity demand; an aggregated V2G service would behave in exactly the same manner, so it follows that the V2G service should be eligible for a capacity payment just as peaking generators are. The problem, however, lies in defining the capacity of a PHEV; capacity for power generators is defined as the maximum amount of power that they can generate, and that amount of power can be generated for an indefinite period of time. This is not the case for PHEV batteries, however, which can produce various amounts of power, but for only as long as the battery lasts. For this reason, we define the capacity of the aggregated V2G service as the amount of electricity load that the V2G service can reduce during a single hour (if the amount of power reduced is large enough that the load during the peak hour is actually below that of its surrounding hours, then the peak reduction is spread over more than 1 h).

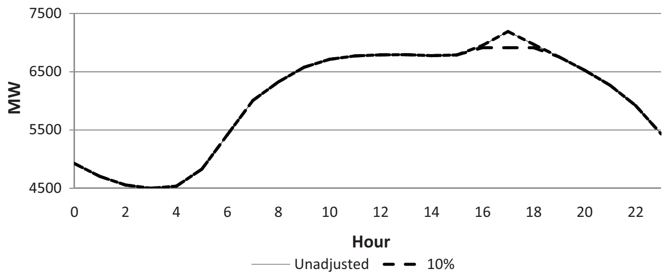

Fig. 1. Unadjusted load and reduced peak load with 10% V2G participation. Data shown is for 1/05/09 (22).

Fig. 1 shows the difference between the unadjusted load and the reduced peak load with 10% V2G participation; the way we defined the capacity of the V2G program, it is the distance between the top of the unadjusted peak and the reduced peak at the same hour. Because we are using hourly load data and assuming low participation rates (lower than 10%), we define the capacity (in kW) for each vehicle as the same number of available kWh that is left on the battery. Note that this would not be the case in higher participation scenarios (such as in Fig. 1), where the period of peak reduction would span more than 1 h. As for the capacity payment itself, we use a value of $50,000/MW, which was approximately the capacity payment that generators in New York City received in 2008 [13]; this value is used for all 3 years that we investigate (2007–2009).

The final two parts of Eq. (1) to define are C_f and C_d. For C_f, we simply use a value of $90 per year, as in [5]. Though that paper was focused on using V2G for frequency regulation, the same technology would be required to use V2G for peak reduction. To determine the cost of battery degradation, we refer to Eq. (2):

$$C_d = \frac{c_b + C_l}{L_c \cdot E \cdot \mathrm{DoD}}, \tag{2}$$

where c_b is the total cost of a new battery; c_l is the labor cost of battery replacement; L_c is the battery lifetime in number of cycles at a certain depth of discharge; E is the total battery energy capacity; DoD is the depth of discharge used in L_c.

Note that in this equation, C_d is the cost of battery degradation in $ per kWh of throughput, which allows for easier interpretation in this type of analysis than would a measure of cost per battery cycle. In Eq. (2), c_b is the total cost of a new battery – we use a value of $300/kWh, which is the target cost for 2015 set by the U.S. Advanced Battery Consortium [14]. This number is multiplied by 16 kWh to determine the total cost of a new battery as $4800. c_l is the labor cost of replacing the battery, which we define as $240 (8 h at $30/h) – this is consistent with previous literature [5]. In the denominator of Eq. (2), L_c is the battery lifetime in cycles at a certain depth of discharge. Because there is some uncertainty about the battery lifetime in terms of cycles, both a lower and upper bound scenario are considered here. In the less generous scenario, we assume a battery lifetime of 1500 cycles at 80% depth of discharge, which is taken from a 2004 study on the aging of batteries [15]. The more generous scenario is based on amore recent study of the performance of PHEV batteries, which predicted that it takes approximately 5300 cycles at 95% depth of discharge before the battery reaches 80% of its original capacity; the level at which it is recommended to replace the battery (note that this is an extrapolation based on their data; it is impossible for an actual battery cycling regime at 95% depth of discharge to continue once a battery is below 95% of its original capacity) [16]. Unfortunately, data was not available for the number of cycles at 50% depth of discharge, which is the maximum depth

Table 2
Energy revenues, costs, and arbitrage profits (2007).

Driver group	Energy revenues	Energy costs	Arbitrage profits
0–10 miles	$364	$148	$216
10–20 miles	$257	$104	$153
20–30 miles	$150	$61	$89
30–40 miles	$65	$27	$39

Table 3
Energy revenues, costs, and arbitrage profits (2008).

Driver group	Energy revenues	Energy costs	Arbitrage profits
0–10 miles	$347	$169	$178
10–20 miles	$245	$119	$125
20–30 miles	$143	$70	$73
30–40 miles	$62	$30	$32

Table 4
Energy revenues, costs, and arbitrage profits (2009).

Driver group	Energy revenues	Energy costs	Arbitrage profits
0–10 miles	$212	$87	$125
10–20 miles	$150	$61	$89
20–30 miles	$87	$36	$52
30–40 miles	$38	$16	$22

Table 6
Annual profits in 2007, 2008, and 2009 – V2G for peak reduction (1500 cycle lifetime).

Driver group	2007 profits	2008 profits	2009 profits
0–10 miles	−$200	−$239	−$291
10–20 miles	−$168	−$195	−$232
20–30 miles	−$135	−$151	−$173
30–40 miles	−$110	−$117	−$126

Table 7
Annual profits in 2007, 2008, and 2009 – V2G for peak reduction (5300 cycle lifetime).

Driver group	2007 profits	2008 profits	2009 profits
0–10 miles	$319	$281	$229
10–20 miles	$199	$172	$135
20–30 miles	$79	$63	$41
30–40 miles	−$17	−$23	−$33

of discharge used by the Chevrolet Volt. In terms of the equation above, L_c is set to 1500 cycles and DoD is set to 80% in one scenario, and L_c is set to 5300 cycles and DoD to 95% in the more generous scenario. The fact that two different depths of discharge are used for the two battery lifetimes should be offset by the fact that the DoD is taken into account in the battery cost equation. E, which is the total energy in kWh of the battery is set to 16 kWh. Solving Eq. (2), we determined the cost of battery degradation to be approximately 26.25¢ per kWh of throughput in the 1500 cycle lifetime scenario and substantially lower at 6.45¢ per kWh of throughput in the 5300 cycle scenario. The 1500 cycle lifetime scenario is included as an extreme high bound for battery costs, and that the 5300 cycle lifetime scenario is actually much closer to reality. Each of the individual components described in Eq. (1) are presented in Tables 2–5 and the total profits earned by participants in a program that uses V2G exclusively for peak reduction are shown in Tables 5 and 6.

Table 6 shows negative profits for all groups. This is primarily due to the fact that the battery cost of 26.25¢ per kWh is actually the higher than the price of energy in most cases. The 5300 cycle life scenario shown in Table 7 suggests that only the individuals who exist in the group who drive the most (and therefore have the least energy to sell to the grid) incur negative profits. The energy and battery degradation costs for this group are very low, since they are not contributing much energy to the grid. The primary reason for the negative profits is the fixed capital cost of $90; the individuals in this driver group could not generate enough revenues from the V2G service to overcome the cost of upgrading their vehicles. The differences in profits through these 3 years are not surprising considering energy prices were at record highs in 2007 and early 2008, then fell considerably with the recession in late 2008. Even with the highest profit figures that we estimate, it is unlikely that these profits would encourage many individuals to participate in this type of V2G program. In the next section, we show that it is far more profitable from the standpoint of the individual to use V2G technology for frequency regulation.

4. V2G for frequency regulation

To determine the revenue that could be earned by supplying frequency regulation, one must take into account both regulation up and regulation down. In our analysis, we assume that half of the time spent providing regulation is on regulation up, and half is spent on regulation down. If we assume that the rate of energy exchange for regulation up and regulation down is equal, this implies that the net change in charge of each battery is zero. At the end of any given regulation session, the battery may end up with a charge that is slightly below or slightly above the charge that was left on the battery at the beginning of the session, but in the long run, the net change in charge will approach zero. Additionally, given a V2G-for-regulation program that is aggregated over many vehicles, the difference would likely be too small to cause a significant impact on any individual driver. In order to describe the revenues associated with using V2G for regulation, we refer to Eq. (3), which is a modified version of the equations used in the previous literature [5,6]:

$$r_{Reg} = (p_{reg} \cdot P) + \frac{1}{2}(p_{el} \cdot P \cdot R_{d-c}), \tag{3}$$

where r_{Reg} is the hourly revenue gained from providing regulation through V2G; p_{reg} is the price of regulation at the specified hour; P is the power rating of the vehicle; p_{el} is the price of electricity at the specified hour; R_{d-c} is the ratio of contracted power to contracted time during regulation-up.

In many energy markets, different prices are given for regulation up and regulation down; in the market in New York, however, only one price for regulation is given. For this reason, only one equation describing the revenues from regulation is required. The first term in Eq. (3) describes the hourly revenue gained through the regulation market. The second term in the equation describes the revenue gained through selling small amounts of electricity to the

Table 5
Capacity payments, battery degradation, and fixed costs (V2G for peak reduction).

Driver group	Capacity payment	Battery cost (1500 cycle lifetime)	Battery cost (5300 cycle lifetime)	Fixed cost
0–10 miles	$356	$683	$163	$90
10–20 miles	$252	$482	$115	$90
20–30 miles	$147	$281	$67	$90
30–40 miles	$64	$122	$29	$90

grid while providing regulation-up. Note that in the previous literature, the same basic formula is used to describe regulation-up, but it is accompanied by another equation for regulation down. Using only one equation and one price for regulation and applying our assumption that half of the contracted time is spent on regulation-up and half on regulation-down, it is necessary to divide the second half of Eq. (3) by two.

We apply Eq. (3) to each hour in the 3 years included in our analysis, then sum over the year. The data we used for our regulation prices is the hour-ahead regulation prices for the East region in New York State taken from the New York Independent Systems Operator (NYISO) [17]. The power rating of the vehicle that we choose is crucial in determining the overall profits from using V2G for regulation. We conduct our analysis for two different power ratings; the first being equal to the charge rate of 1.33 kW that was described previously. In the context of a PHEV, providing regulation-down is the same as charging the vehicle, and thus the capacity for providing regulation-down is limited by the charge rate of the vehicle. We assume that this limitation extends to regulation-up as well. We also present results for a charge rate of 10 kW, as in [6], which implicitly assumes that faster charging technology will be available by the time V2G technology is ready for deployment. The electricity prices that are used here are the same LBMPs that were used in the previous section. Finally, we set the R_{d-c} term equal to 0.10, as in the previous literature [5,6].

Furthermore, to more accurately estimate annual revenues, an hourly measure of vehicle availability is required. To do this, we use data from the Regional Travel-Household Interview Survey (RT-HIS) in the New York Metropolitan Area to determine the percentage of commuter vehicles that are parked and available for V2G at each hour [18]. The RT-HIS provides data on the percentage of commuters going to and from work at each hour; if we assume that each commuter that is going to work then spends 8 h working, and that all of the people who are not either commuting or at work are parked at home, then we can calculate an approximate measure of the percentage of individuals who are parked either at work or at home (and are presumably available for V2G) at each hour. Although this does not provide an actual driving pattern of any real individual, it provides us with a measure of vehicle availability for the "average" individual. The minimum availability is approximately 77.9% at 6 a.m., and the maximum is approximately 99.8% at 1 a.m. Over the 24 h period, the availabilities sum to approximately 22 h.

Fig. 2 helps to illustrate the motive behind using hourly vehicle availability; we could have simply come up with a measure for average hourly revenue and multiplied by 22 h, but this would provide somewhat of an overestimate since the hours of lowest vehicle availability tend to coincide with the hours with the highest prices for regulation. On the other hand, if we were to assume zero availability during the commuting hours and 100% availability during the remaining hours, this would result in an underestimate since commuting hours tend to be the hours with the highest regulation prices. To determine the total annual revenue obtained through the V2G-for-regulation program, we multiply the hourly revenues described in Eq. (3) by the percentage of available vehicles at each hour, then sum over the year; these revenues are shown in Table 8.

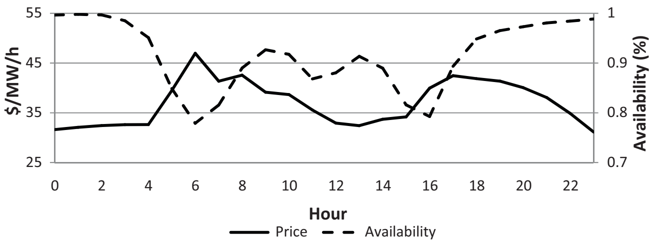

Fig. 2. Average hourly regulation prices for the East region in New York State in 2009 and hourly vehicle availability percentages.

Table 8
Regulation revenues (2007, 2008, and 2009).

Power rating	Revenue (2007)	Revenue (2008)	Revenue (2009)
10 kW	$4780	$4666	$3203
1.33 kW	$637	$622	$427

The way we describe the cost of using V2G for frequency regulation is very similar to the way we described the cost of using V2G for peak reduction. The costs are separated into three categories: fixed costs, energy costs, and the cost of battery degradation. Because the same basic technology is needed for the vehicle upgrade, we assume that the fixed costs are exactly the same as they were in the previous section: $90 annually. The energy cost associated with using V2G for regulation is the cost of purchasing energy that will later be sold to the grid while the vehicle is providing regulation-up. Given the assumption of a net zero change in charge, however, the energy that is sold to the grid is exactly offset by the "free charging" experienced while providing regulation down; thus, the net cost of energy is zero.

There are some uncertainties when estimating the costs of battery degradation specifically in the case of V2G for regulation. The reason for this uncertainty is that the nature of regulation implies that the battery will experience repeated charging and discharging in rapid succession. This repeated charging and discharging can alternatively be viewed as shallow cycling; it has been shown that shallow cycling can actually dramatically increase the cycle life of a battery compared with deep cycling. Test data shows a battery lifetime of a lithium-ion battery of 3000 cycles at 100% depth of discharge, and 1,000,000 cycles at 3% depth of discharge [5]. New data shows that the relationship between depth of discharge and cycle life may not be quite as strong [16]; the data in this study, however, shows that while there may not be such large cycle lives at very shallow depths of discharge, there may be higher than predicted cycle lives at deeper depths of discharge (5300 cycle lives at 95% DoD). To be consistent with previous studies [5,6], we use a scaling factor of three for the shallow depths of discharge associated with using V2G for regulation, and test both the 1500 and 5300 cycle life scenarios. This means that the shallow discharging results in three times the cycle life, and thus one third of the cost in dollars per kWh of throughput when compared with deep discharging. The cost of battery degradation in the 1500 cycle life scenario is 8.75¢ per kWh of throughput and 2.01¢ per kWh of throughput for the 5300 cycle life scenario. We are able to calculate annual vehicle throughput by using the vehicle availability percentages along with $P{\cdot}R_{d-c}$ from Eq. (3); from there we are able to quantify the costs of battery degradation. The annual battery degradation costs for the 10 kW and 1.33 kW scenarios are $702.63 and $93.68 for the 1500 cycle life scenario and $167.46 and $22.33 for the 5300 cycle life scenario. These costs, along with the $90 fixed cost are subtracted from the annual revenues to derive the annual profits shown in Tables 9 and 10.

We show here that even with the least generous assumptions (even with extremely high battery costs), the profits derived from participating in a V2G for regulation program are greater than the highest profits earned in a program that uses V2G for peak reduction in the same year. In the next section, we propose a way in which we can keep the higher profits that are realized by using V2G for regulation intact, while still achieving some of the external benefits associated with peak reduction by only using V2G for peak reduction on the days when it is needed most.

Table 9
Annual profits for 2007, 2008, and 2009 – V2G for regulation (1500 cycle lifetime).

Power rating	2007 profits	2008 profits	2009 profits
10 kW	2410	4075	4118
1.33 kW	243	465	470

5. V2G for regulation and peak load reduction

When it comes to using V2G technology for peak load reduction, there are limited financial incentives for the driver. That being said, there is potential for significant external benefits if V2G is used for peak reduction during times of high electricity demand. These external benefits come in the form of cost savings for the grid operators, who may be able to decrease the use of expensive and inefficient generators. Additionally, and perhaps most importantly, there are also significant environmental benefits that can be experienced. Periods of high electricity demand typically happen during hot summer days; the damage from additional power plant emissions on these days tends to be exacerbated by the atmospheric conditions during these times, which are conducive to the formation of certain air pollutants, such as ozone [4].

Because of the higher profits that are available, we will operate under the assumption that V2G participants are exclusively providing regulation for most days of the year. That being said, we also assume that they are always available to sell energy to the grid for the purpose of peak reduction. In a sense, they will end up acting like a traditional peaking generator that only produces electricity when the demand is extremely high. In reality, the times that PHEVs would be used to provide peak-reducing energy to the grid would ultimately be up to the grid operator or ISO, but for the purposes of our analysis, it is necessary to specify these times. We will assume that V2G is used for peak reduction only on ozone exceedance days. Using this as a benchmark, we will calculate the annual profits for a V2G participant in this type of program.

An ozone exceedance day is any day when the measured average ambient ozone concentration is above the federal standard (National Ambient Air Quality Standard) of 8-h averaged 0.075 ppm or 1-h averaged 0.12 ppm. In our analysis, we consider any day that registered an 8-h ozone exceedance at any of the New York Metropolitan Area monitoring stations (there are nine). In 2009, there were nine such ozone exceedance days in the New York Metropolitan Area: 26-April, 22-May, 7-June, 16-July, 10-August, 16-August, 17-August, 26-August, and 5-September [19]. Additionally, there were 18 exceedance days in 2008 and 11 days in 2007. In reality, using ozone exceedance days as a benchmark is only useful in retrospect. If this type of program were to be actually implemented, a different system, likely using day-ahead air quality forecasts, would be required to signal for the use V2G as peak reduction.

With specific days identified for the use of V2G for peak reduction, it is then possible to estimate the potential profits of a participant in this type of program. The bulk of the profits still come from using V2G for frequency regulation during 356 days of the year (365 minus nine exceedance days). This means that the profits for these 356 days can be computed exactly as they were before. This, however, does not represent all of the profits from V2G for regulation because we assume that even during exceedance days that the participants are providing regulation until the time that they sell their excess energy for the purpose of load reduction. Because of this, there will be several hours during which the V2G participants will provide regulation on exceedance days: from 6 a.m. (the time the vehicle is assumed to be fully charged) until the time at which their excess energy will be sold to the grid. As expected, the annual revenues and battery degradation costs are only slightly lower for the regulation component. (Note that both the 1500 and 5300 cycle battery life scenarios are considered.)

When calculating the profits associated with energy arbitrage, we looked at the nine individual exceedance days and calculated the price difference for each day. Using these price differences, we were able to calculate the profits from energy arbitrage over the 9 days. To calculate the cost of battery degradation, we needed to determine the electrical throughput during both peak reduction and regulation, and then multiply by the associated price. Additionally, the fixed capital cost of $90 is taken into account in each scenario.

The last component to take into account is the capacity payment. Because the vehicles would be available to supply energy to the grid year-round, there is no reason to believe that they would not be eligible for the full capacity payment as described in Section 3. In the type of program being discussed here, the V2G participants would essentially be operating in the same manner as a peaking power plant. Just like our proposed V2G program, many of these peaking power plants do not operate for more than a few days throughout the year, which follows that a V2G program behaving in a similar manner would be eligible for similar compensation. The final annual profits for our proposed V2G program are shown in Tables 11–16.

Notice that some of the profits for the dual-use V2G program are actually higher than the profits for either single-use program on their own in 2009. The reason that the profits are higher than the

Table 10
Annual profits for 2007, 2008, and 2009 – V2G for regulation (5300 cycle lifetime).

Power rating	2007 profits	2008 profits	2009 profits
10 kW	$4656	$4616	$2951
1.33 kW	$543	$537	$316

Table 11
2007 annual profits – dual use V2G program (1500 cycle lifetime).

Driver group	Annual profits – 10 kW	Annual profits – 1.33 kW
0–10 miles	4091	773
10–20 miles	3988	670
20–30 miles	3884	566
30–40 miles	3802	484

Table 12
2007 annual profits – dual use V2G program (5300 cycle lifetime).

Driver group	Annual profits – 10 kW	Annual profits – 1.33 kW
0–10 miles	$4629	$711
10–20 miles	$4521	$603
20–30 miles	$4412	$495
30–40 miles	$4327	$409

Table 13
2008 annual profits – dual use V2G program (1500 cycle lifetime).

Driver group	Annual profits – 10 kW	Annual profits – 1.33 kW
0–10 miles	3939	743
10–20 miles	3838	643
20–30 miles	3738	542
30–40 miles	3659	469

Table 14
2008 annual profits – dual use V2G program (5300 cycle lifetime).

Driver group	Annual profits – 10 kW	Annual profits – 1.33 kW
0–10 miles	$4478	$837
10–20 miles	$4370	$729
20–30 miles	$4262	$621
30–40 miles	$4177	$536

Table 15
2009 annual profits – dual use V2G program (1500 cycle lifetime).

Driver group	Annual profits – 10 kW	Annual profits – 1.33 kW
0–10 miles	2542	558
10–20 miles	2442	457
20–30 miles	2341	356
30–40 miles	2261	277

V2G for regulation program by itself is that the V2G system is only being used for peak reduction on a very limited number of days, and the additional capacity payment received more than makes up for the lost revenues that are experienced when the vehicles are being used for peak reduction rather than regulation. In 2007 and 2008, where there were more exceedance days, and thus more days where the V2G program was being used for peak reduction, even the highest profits in the combined program are lower than that of either of the single-use program. This is not necessarily a problem, however, since the profits only need to be high enough to incentivize people into participating in the program. In fact, with more days being used for peak reduction, the profits to the individual may be lower, but the external benefits could be higher. An unexpected long-run problem is possible if the profits are actually too high, and too many people want to participate in the program. The implications of high participation scenarios are discussed in the next section.

6. High participation scenarios

With higher levels of participation in a V2G program, there is potential to offset more peaking load and to provide a higher levels of regulation capacity. The problem with high levels of participation, however, is that we expect the revenues to the individual drivers will decrease. This is true for either of the single-use V2G programs that we have discussed, and is thus true for the dual-use program that we have proposed. First, in the case of V2G for peak reduction, we expect that revenues will decrease from both the energy and capacity markets.

In the energy market, high levels of participation will mean significantly reduced load during peak hours, which is the goal of the peak reduction strategy. The problem with this, however, is that lower loads translate into lower electricity prices during the times that V2G participants will be selling their energy to the grid. Additionally, higher levels of PHEV penetration will mean more people charging their vehicles at night, and thus higher real-time electricity prices for charging. Higher prices during charging and lower prices during vehicle-to-grid discharging translates into decreased profits from the energy market. To estimate the magnitude of this effect, a multiple variable autoregressive integrated moving average (ARIMA) model is used to determine the impact of changes in electricity load on electricity price in New York City. The detailed description of this model can be found in Supporting Information. The difference in profits under four different load scenarios were estimated using this model. The first scenario uses unadjusted loads (but model predicted prices), the second assumes 25% PHEV penetration, and within those PHEVs, 25% V2G participation (such that 25% of all vehicles are PHEVs, and 6.25% of *all* vehicles participate in the V2G program). The next scenario assumes 50% PHEV penetration and 50% V2G participation, and the final scenario assumes 50% PHEV penetration and 100% V2G participation. The load profiles of each day of the year in 2008 were adjusted to reflect these conditions so that adjusted hourly prices for the entire year could be estimated. Fig. 3 shows the average electricity load at each hour throughout the year under each of these four scenarios.

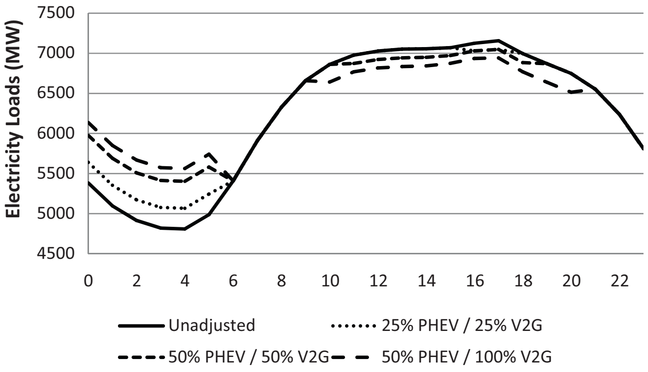

Fig. 3. Adjusted average electricity loads.

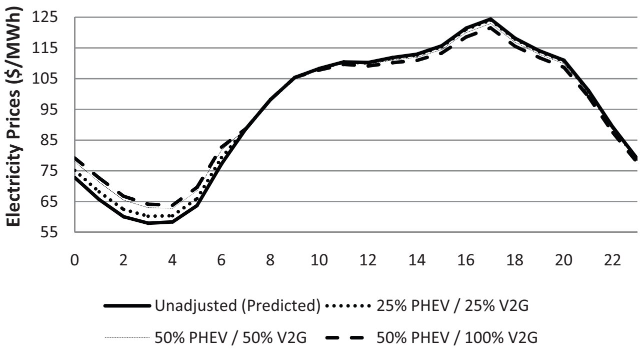

Fig. 4. Adjusted average electricity prices.

Fig. 3 shows that with higher levels of PHEV penetration and V2G participation, the electricity load increases during the night (the hours of regulated charging), and decreases during the peak hours. Notice that with very high levels of participation, the number of hours over which V2G discharging is spread increases. Additionally, even with the PHEV penetration remaining the same, at higher V2G participation, there is more electricity required even for charging (this is because the electricity discharged through V2G needs to be charged as well). Using these adjusted loads, hourly electricity prices are estimated for each hour of the year in 2008; the average hourly electricity prices are shown in Fig. 4.

Using the adjusted hourly prices represented by Fig. 4, the energy arbitrage profits for each scenario can be estimated; these are shown in Tables 17–20.

The estimates shown in show that with increased PHEV penetration and V2G participation, the costs of participating in the program increase, and the revenues and profits decrease. While this is true, the profits gained from energy arbitrage do not decrease by an extremely large amount; even with 50% of all vehicles participating in a V2G program, the profits are only reduced by approximately $23.

Table 16
2009 annual profits – dual use V2G program (5300 cycle lifetime).

Driver group	Annual profits – 10 kW	Annual profits – 1.33 kW
0–10 miles	$3080	$640
10–20 miles	$2975	$536
20–30 miles	$2871	$432
30–40 miles	$2788	$346

Table 17
Energy revenue, costs, and arbitrage profits – unadjusted loads.

Driver group	Revenues	Costs	Arbitrage profits
0–10	$334	$165	$170
10–20	$236	$116	$120
20–30	$138	$68	$70
30–40	$60	$30	$30

Table 18
Energy revenue, costs, and arbitrage profits – 25% PHEV/25 V2G.

Driver group	Revenues	Costs	Arbitrage profits
0–10	$334	$171	$163
10–20	$236	$120	$115
20–30	$137	$70	$67
30–40	$60	$31	$29

Table 19
Energy revenue, costs, and arbitrage profits – 50% PHEV/50% V2G.

Driver group	Revenues	Costs	Arbitrage profits
0–10	$331	$178	$153
10–20	$234	$126	$108
20–30	$136	$73	$63
30–40	$59	$32	$27

Another problem could arise from decreased capacity payments. We defined the capacity of the aggregated V2G program as the amount of electricity load that can be reduced through the use of the V2G program. With the hourly load data that we use here, this means that if there is enough V2G capacity that the peak reduction can be spread over more than 1 h, then the capacity for each participant in the V2G program will be reduced. If real-time data were used (as might be used in an actual system), then a much smaller increase in the time scale of the peak reduction would result in decreasing marginal capacity. To give an idea of the magnitude of this effect in terms of our study, we calculated an annual capacity payment for a V2G participant in the lowest mileage group (0–10 miles) of $356.19 at 1% participation, where the peak reduction only occurs in only a single hour, and $264.25 at 10% participation, where the peak reduction occurs over 3 h. One could argue that the problem discussed here is simply a symptom of the way we define the capacity of the V2G service, and this could be true, but it is something that needs to be considered when structuring payments for any type of storage system used to reduce the peak electricity load. We are trying to do this within the framework of the electricity markets that exist today, but perhaps what is actually needed is a formal market for storage. There is some evidence of this need in the California energy market, where Western Grid Development LLC requested that its storage devices be classified as wholesale transmission facilities and be eligible for rate-based regulation [20]. This would most likely be unnecessary if there were a formal market for electricity storage.

What is perhaps the most serious problem that can occur with high rates of participation has to do with regulation. The problem lies in the fact that only a certain amount of regulation capacity is needed for the system. In California, the regulation requirements range between 5% and 10% of the load at any given time [21]. If we apply this to the New York City electricity market, which had an average load of 6062 MW in 2009 [22], then the amount regulation capacity needed would be on the order of 303–606 MW. To fulfill 606 MW worth of regulation capacity in the New York Metropolitan Area would require approximately 5.4% participation assuming a 10 kW power rating, and 40.2% participation with a 1.33 kW power rating. If the amount of regulation capacity provided by the V2G service grows beyond the level that is required, then regulation prices will likely sharply decrease (in a competitive market). Alternatively, if prices are controlled, then many regulation-providing generators and V2G participants would be crowded out of the market.

Table 20
Energy revenue, costs, and arbitrage profits – 50% PHEV/100% V2G.

Driver group	Revenues	Costs	Arbitrage profits
0–10	$327	$181	$147
10–20	$231	$128	$104
20–30	$135	$74	$60
30–40	$59	$32	$26

There are reasons to believe that there is more room for regulation-providing V2G participation than our numbers suggest. For example, it is likely the levels of V2G regulation capacity required will be higher than the amount of V2G regulation capacity that is used, in order to ensure reliability, as suggested in [6]; note that this would also have the detrimental effect of reducing the profits to the individual participants. It is suggested by Quinn et al. [6] that the amount of regulation capacity required would be approximately 2.49 times greater than the amount that would actually be used, which implies that the profits would be scaled back by an equivalent amount. Additionally, the only ancillary service market that we have considered is regulation, but there are other markets (such as the reserves market) in which a V2G service could make a valuable addition; with high rates of participation, the aggregated V2G service could participate in multiple markets. Furthermore, it is likely that there will be significantly increased demand for regulation, reserves, and storage due to higher penetrations of intermittent renewable energy sources such as wind and solar.

7. Conclusions

The results of our economic analysis suggest that there is little financial incentive for PHEV owners to participate in a program that uses V2G technology solely for peak reduction. On the other hand, we found that there is significant potential for financial return for the participants when V2G technology is used for regulation. Therefore, we proposed that with a program using V2G technology for regulation on a daily basis and for peak reduction on high electricity demand days, profits for the participants may be higher than either of the two single-use programs on their own. More importantly, we believe that this type of dual-use V2G program has the potential to reduce environmental damages while keeping the profits to the individual participants at a level that will induce participation.

The estimates that we have produced in this study are based on the assumption that a V2G program would operate in the market as it is set up today. As such, we found that there is a tendency for revenues to decrease (both in terms of V2G for regulation and V2G for peak reduction) as participation in the V2G program increases. In terms of V2G for peak reduction, we suggest that there may be a need to create formal storage markets, especially as the need for storage will increase with higher penetrations of intermittent renewable technologies. In terms of V2G for regulation, we suggest that at higher participation rates the market for regulation capacity could become saturated by V2G-based regulation providers. That being said, we do believe there is plenty of potential for widespread use of V2G technology, especially if the demand for regulation, reserves, and storage grows as we expect.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jpowsour.2010.11.010.

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