The potential of plug-in hybrid and battery electric vehicles as grid resources: the case of a gas - and petroleum –oriented electricity generation system

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Introduction and Overview

A number of automobile manufacturers are currently introducing electric drive vehicles (EDVs) to the automobile mass market. EDVs come in the form of plug-in hybrid electric vehicles (PHEVs), such as the General Motors Volt, and battery electric vehicles (BEVs), such as the Nissan Leaf. Each type of EDV uses an electric motor to convert electrical energy into mechanical traction, with the electrical energy derived from the electricity grid and stored in a battery. In the case of PHEVs, a conventional gasoline-powered engine complements the electric drive train to allow for trips longer than the vehicle's battery capacity will allow.

Previous research has shown that EDVs offer a number of potential complementarities to the conventional system of electric power generation, transmission, and distribution. They could conceivably be used to store electric energy in their batteries during times of the diurnal cycle when cost of generating electricity is low, and then discharge the stored electricity back into the grid during times of peak demand when the cost of generating electricity is high. We will refer to this as "peak shaving," although our usage here is not exactly in keeping with electricity industry nomenclature. As reported by Kempton and Letendre (1997), on average passenger vehicles used in the United States are parked 96% of the day. Therefore, they are potentially available for most hours of the day for peak shaving, provided that the appropriate infrastructure was in place to integrate their battery storage and internal vehicle electronics into the grid.

Another potential benefit that EDVs offer to the electric power production system is providing reserves services. Reserves services are a power source's ability to quickly feed electricity into the grid whenever a conventional electricity generator unexpectedly trips off. In order for EDVs to perform this function, it would be necessary for hundreds of them to act in concert at a time of an unexpected failure of a conventional generator, something that can be conceivable in the near future as EDV use rises. This, in turn, would require that each vehicle be equipped with vehicle-to-grid (V2G) technology (a technology already in existence) so that the central dispatcher for the power system could feed their battery power into the grid. EDVs are well suited for such a task as the vehicle battery and on-board electronics of an EDV have a very high ramp rate, meaning that the power output from the vehicle can be increased from zero to several kilowatts in less than one second. This technical characteristic helps to make them suitable for quick-start reserves services.

The third avenue through which EDVs could enhance the economics of an electric power grid is in the area of frequency regulation services. Frequency regulation, currently undertaken by one or more conventional power generators on the grid, involves the generator minutely throttling-up and -down its power output in order to match random upswings and downswings in electricity demand (load) on the system. The former is referred to as "regulation up," and the latter as "regulation down." Frequency regulation keeps total generation in balance with total load, which entails that the AC frequency on the grid remains tightly bound to its targeted level, e.g. sixty cycles per second in the case of power grids in North America. There is no reason why a fleet of EDVs could not provide regulation services while plugged into the grid, provided that the flows out of and into their batteries could be controlled by central dispatch through V2G technology. This would lessen the need for conventional generators to serve this function. Kempton et al (2008) report on a demonstration project indicating the technical feasibility and utility of such an undertaking.

Using publicly available data pertaining to the Long Island Zone of the New York Independent System Operator (NYISO), this paper focuses on the economics of using EDVs for peak shaving, along with the ancillary services of reserves and regulation, in the wholesale market for electricity in the Long Island Zone. The Long Island Zone of NYISO differs markedly from the wholesale electricity markets used in previous studies in this area in that the former relies more heavily on natural gas and petroleum-fired combustion turbine generators than the markets examined in other studies. This entails that the difference between peak and off-peak wholesale prices in the Long Island Zone is not as great as it is in many other markets. In addition, the wholesale electricity market on Long Island places a greater value on frequency regulation services than most other wholesale electricity markets.

We begin with a literature review of previous studies, and then move on to examine the economics of peak shaving by EDVs in Long Island. Next, we will cover the revenue and cost streams of using EDVs for reserves and regulation services. Following this, the article will explore some potential market problems that could arise if EDV owners were to act independently and competitively with one another as they offer bids to provide regulation services, and how these problems suggest that a competitive market would fail to provide vehicle owners with an incentive to offer regulation services.

Review of Existing Literature

Kempton and Letendre (1997), and Kempton et al. (2001) are among the first to comprehensively analyze the possibilities for using EDVs to enhance the performance and economics of an electricity grid. More recently, Kempton and Tomic (2005a) have undertaken a detailed analysis of the potential profitability of using an EDV's battery and electronics capacity in segments of electricity markets using contemporary parameters pertaining to EDV battery technical characteristics. In a related article, Kempton and Tomic (2005b) propose various business models and regulatory policies that could spur the adoption of EDVs for grid services. Tomic and Kempton (2007) examined how an owner of a fleet of EDVs stands to profit under certain circumstances from using the fleet to provide regulation services. Sioshansi and Denholm (2009a; 2010) explore economic and environmental benefits of integrating EDVs into the grid, focusing on enhancements in generator performance and dispatch rather than the potential profitability to the vehicle owner

The possibility of using EDVs for peak shaving has been considered previously, however not in considerable depth (Zorpette 2004; Ferdowsi 2007). Kempton and Tomic (2005a) examined the use of a hydrogen fuel cell vehicle, but not a PHEV or BEV, for selling electricity into the grid during times of peak prices. Using a hydrogen fuel cell vehicle for peak shaving would not entail purchasing electricity off the grid during off-peak hours of low demand and prices. Thus, the peak shaving analysis undertaken in this paper differs somewhat in its approach from that of Kempton and Tomic (2005a). Kempton and Tomic (2005a) also simulate the economics of using a hydrogen fuel cell vehicle, but not a PHEV or BEV, to provide reserves services. The use of PHEVs for peak shaving is assessed by Sioshansi and Denholm (2010). However, because they only consider PHEVs, which have a far smaller battery energy storage capacity than BEVs, they find adverse impacts on the economics of peak shaving by EDVs.

Kempton and Tomic (2005a) analyzed a hypothetical case of frequency regulation provided by a BEV in the context of price data from the California Independent System Operator (CAISO), and found that the vehicle owner would stand to profit from $1731 to $2554 per year, depending on the capacity of the power line leading into the house. The profitability of using an EDV to provide regulation services is supported by Tomic and Kempton (2007) This paper applies the analytical approached developed by Kempton and Tomic (2005a) and Tomic and Kempton (2007), with minor modifications.

Peak Shaving

As EDVs store electrical energy in their batteries and V2G technology would allow them to interface in real time with the electricity grid, it may seem at first glance that if the vehicle owner were allowed to participate in the day-ahead wholesale electricity market, he or she may be able to profit by purchasing electricity in off-peak hours and contracting to resell during peak hours. Between the times of purchase and sale, electrical energy would be stored in the vehicle's battery. In order to do this, the car could not be driven at either the time that it is charging off the grid or discharging back into the grid, and for no substantial time in between. The EDV could be used for diurnal price arbitrage only on days when it is barely driven or not driven until after the afternoon peak.

Data from the Long Island Zone suggests that the owner of an EDV would stand to profit from using the car for peak shaving (Figure 1). The wholesale price of electricity in the Long Island Zone is considerably higher during peak hours than in non-peak hours. In light of the gap between wholesale electricity prices in the early a.m. hours and in the mid-p.m. hours, the owner of an EDV might be tempted to purchase some kilowatt-hours during the former period, store them in the vehicle's battery, then resell into the market during the later period.

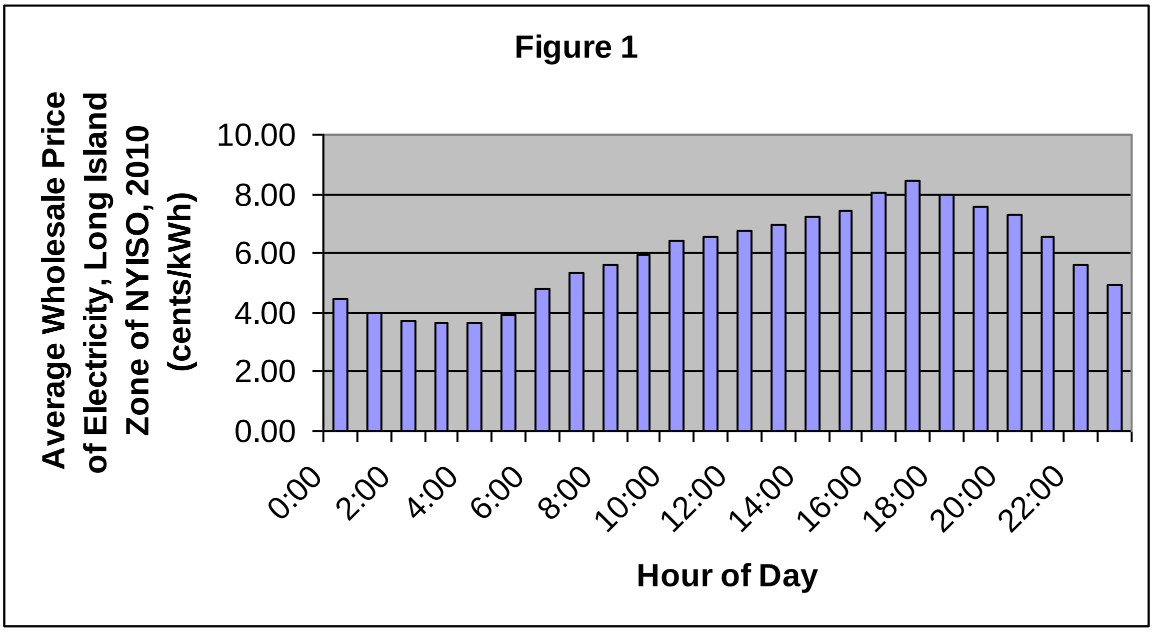

Figure 1. Average wholesale price of electricity in Long Island Zone in 24 hour period (data available upon request).

There are a number of considerations against the economics of using an EDV for peak shaving. One is conversion losses, where electrical energy is lost when transferred from the grid to the battery, and then again when discharged from the battery back into the grid. Sioshansi and Denholm (2009b) posit a 10% electrical energy loss when charging the battery of an electric drive vehicle, and a 7% loss when discharging. In order for the vehicle owner to break even, the price received when discharging into the peak hours must be approximately 120% times the prices when the electricity was purchased.

Another consideration is the significant battery depletion costs incurred from deep-cycling the lithium-ion battery of an EDV. The service life of a lithium-ion decreases exponentially with the depth to which it is typically discharged before being recharged. According to Sioshansi and Denholm (2010), a lithium-ion battery used in an EDV can be cycled approximately 12,000 times over its lifetime at a 40% depth-of-discharge, but only 2,500 times at an 80% depth-of-discharge. Peak shaving would inherently involve non-trivial cycling of the vehicle battery, for otherwise only a trivial amount of electricity could be transferred from the off-peak to the peak hours. Consequently, the battery depletion cost per kWh transferred could be considerable.

To estimate the battery depletion cost of peak shaving, we note that the United States Advanced Battery Consortium has set long-term research and development goals for batteries in EDVs of 40 kWh for battery pack energy storage capacity, and $100/kWh for the cost per unit of energy storage capacity (United States Advanced Battery Consortium 2010). The total lifetime throughput of a 40 kWh lithium-ion battery pack would then be 192,000 kWh and 80,000 kWh under a 40% and an 80% depth-of-discharge cycling regime, respectively. Therefore, the battery depletion cost per kWh transferred from off-peak to peak hours would be 2.1¢ per kWh and 5.0¢ per kWh under a 40% and an 80% depth-of-discharge cycling regime, respectively. The relative battery depletion cost might make the 40% cycling regime more attractive than the 80% regime for peak shaving.

A final consideration is that residential power line constraints would limit the amount of electricity that could be transferred from EDV to power grid. This means that at least some of the electricity purchased off the grid would most likely be purchased at a price above its lowest price, and sold into the grid at a time other than the hour when price is at its maximum. Let us assume a residential power line available capacity of 10 kW (a capacity that may entail some wiring upgrades), meaning this much capacity is not being used for other household uses at the times that electricity is being purchased off the grid or sold back into it.

Using the aforementioned technical assumptions, a quick analysis of the data in Figure 1 reveals that, on an “average” day in 2010, the owner of an EDV who used it for peak shaving and kept the depth-of-discharge to the battery to 40% would have generated a profit of only 22 cents. This calculation ignores the capital cost of necessary wiring and vehicle electronics upgrades. In order to generate this maximum daily profit of 22 cents, the vehicle owner would have purchased 10 kWh off the grid at a price of 3.6¢/kWh between 3:00 a.m. and 4:00 a.m., bringing the energy stored in the battery from 24 kWh to 33 kWh, after conversion losses entailed by charging. The owner would then have purchased another 7.78 kWh at a price of 3.7¢/kWh between 4:00 a.m. and 5:00 a.m., bringing the energy stored in the battery up to 40 kWh. Beginning at 5:00 p.m., when hourly wholesale electricity prices hit their daily peak on an average day, the vehicle owner would have sold 10 kWh into the grid between 5:00 p.m. and 6:00 p.m. at a price of 8.5¢/kWh, which leaves 29.3 kWh of energy remaining in the battery after discharging conversion losses. Another 4.95 kWh would have been sold in the next hour at a price of 8.0¢/kWh, leaving 24 kWh of energy stored in the battery. Allowing the depth-of-discharge to reach 80% would let the vehicle owner earn a greater profit on an average day than a 40% depth-of-discharge. However, the significantly higher battery depletion cost per kWh transferred under the 80% depth-of-discharge scenario entails that it would be impossible to generate a profit in this scenario.

One reason why the peak shaving simulation results found here are so discouraging is that 2010 was a fairly typical year, compared to other recent years, in terms of the prices of fossil fuels used to generate electricity, and in the differences between off-peak and peak wholesale electricity prices. 2010 did not witness the abnormally high fossil fuel prices and gaps between off-peak and peak electricity prices that occurred in 2008, nor the abnormally low ones that prevailed in 2009.

It is clear that in a wholesale electricity market with pricing patterns similar to those in the Long Island Zone, which is far more dependent on natural gas and petroleum for electricity generation than most other regions, using an EDV for peak shaving does not make economic sense. Our results are thus in line with Sioshansi and Denholm (2010) who using data from the Electricity Reliability Council of Texas, which is more dependent on coal for electricity generation, also demonstrate that using PHEVs for electricity sales into the peak market is uneconomic due primarily to the cost of deep-cycling the vehicle battery. It is difficult to imagine a Long Island vehicle owner sinking several hundreds of dollars installing V2G technology, upgrading a residence, and only recouping a couple cents a day from peak shaving only on those days when the car's use is limited between the early a.m. hours and about seven o'clock in the evening.

Reserves Services

The technical characteristics of EDVs, especially their ability when equipped with suitable V2G technology to rapidly ramp-up and ramp-down power that they feed into the grid, creates the potential for them to serve as suppliers of synchronized reserves and frequency regulation services to a wholesale electricity market. We turn first to their potential use for reserves services in the wholesale market for electricity on Long Island.

The reliability of an electrical grid hinges on a certain level of power generation being held in instantaneous reserve. A breakdown of a generating station can happen unexpectedly and at any time. If there is an insufficient quantity of backup power generation available at no more than a few seconds' notice to make-up for the lost power by the failed generator, the total supply of power into the grid will fall short of the total load on the system. In the case of the NYISO market, the system operator purchases three types of reserves in the wholesale ancillary services market to forestall a system failure caused by a generator unexpectedly tripping off the system. One type is ten-minute synchronized reserves where power output is synchronized to the AC current in the grid, which can ramped up to maintain a higher level of power output for ten minutes after being called upon by the system operator to do so. The second type of reserves is ten-minute non-synchronized reserves, which are generators with power output that can be synchronized to the grid and maintain high power output for ten minutes. Ten-minute non-synchronized reserves are not expected to meet the targeted power level as quickly as synchronized reserves. The last types of reserves in the NYISO market are 30 minute non-synchronized reserves, which are essentially the same as the 10-minute non-synchronized reserves, but are capable of maintaining their higher output levels for a longer period of time.

EDVs are suitable for providing synchronized reserves, primarily because they provide immediate power capacity. The ramp rate for the battery and internal wiring is extremely high, which allows the vehicle to quickly boost the power it is supplying to the grid. In addition, since a provider of reserves services is seldom called upon to inject power into the grid, the battery cycling cost incurred from providing this service would be negligible. On those rare occasions when a reserves provider is called upon to inject power into the grid, the provider is paid an energy payment in addition to the reserves power capacity payment received regardless of whether it is actively feeding power into the grid. The revenue stream to a provider of reserves services consists almost exclusively of payments for providing quick-start power capacity, rather than energy payments.

In the NYISO market, generators are allowed to bid reserves capacity into the day-ahead markets for 10 minute synchronized, 10 minute non-synchronized, and 30 minute non-synchronized reserves. The 10 minute synchronized reserves command by far the highest price of the three, and we will focus on this type of reserves here. The value of 10 minute synchronized reserves tends to vary considerably over the course of the day, with reserves commanding a much higher price during peak hours than the non-peak hours (Figure 2). We label the unit of measure for reserves services as kW-h, which means one kilowatt of power capacity supplied for one hour. This, of course, is not the same concept as the unit of measure for energy, kWh, which is one kilowatt of power lasting for one hour. Figure 2 demonstrates that the diurnal pattern of reserves pricing dilutes the potential profitability of offering an EDV into the reserves market. The value of the service is highest at times when the vehicle is most likely to be used for transportation and thus not be plugged into the grid, and lowest when the vehicle is most likely to be available to provide reserves.

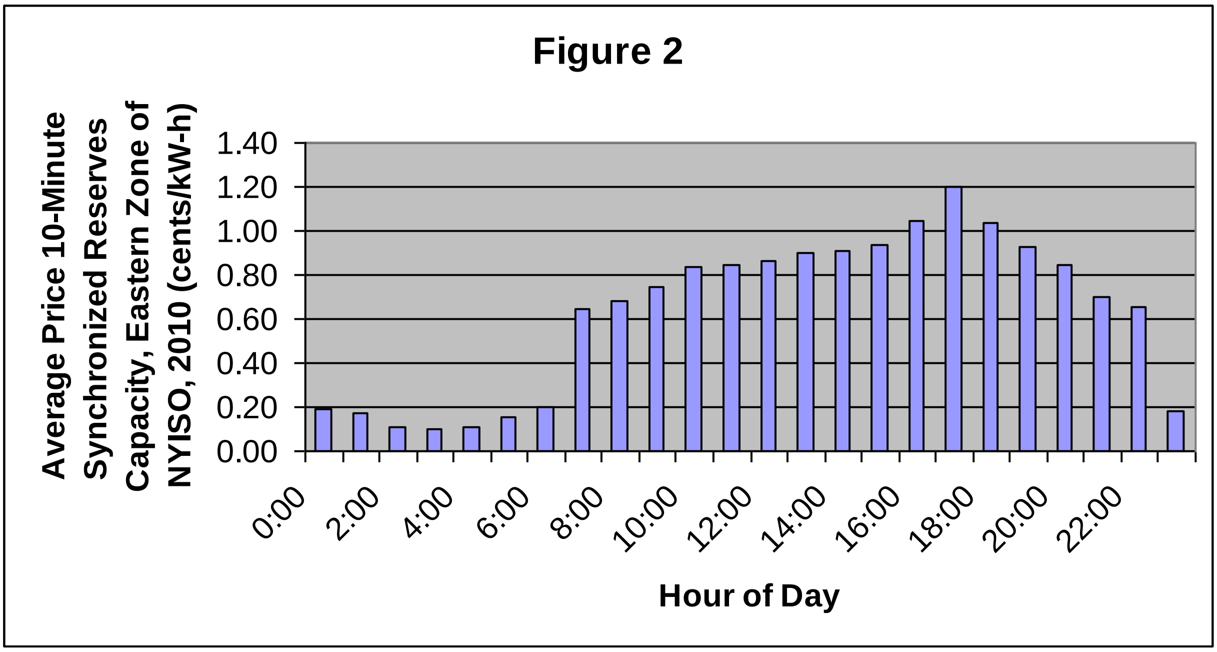

Figure 2. Average price for 10-minute synchronized reserves capacity (data available upon request).

To estimate the profitability of using an EDV for reserves, we assume that the vehicle would be plugged into a V2G-compatible power source on a year-round average during 95% of each hour beginning between 0:00 and 6:00, 25% of each hour beginning between 7:00-8:00, 50% of each hour beginning between 9:00-15:00, 25% of each hour beginning between 16:00-17:00, and 80% of each hour beginning between 18:00-23:00. The owner of the vehicle would receive a power capacity payment, based on the rates in Figure 2, for each hour that the vehicle is plugged in. In order to calculate the revenue stream from providing reserves we must also take into the consideration the expected energy payments from providing reserves. Following the methodology of Kempton and Tomic (2005a), we calculate the annual revenue stream for the vehicle owner providing reserves into the NYISO reserves market, which consist of both the capacity payments and the energy sales.

The annual revenue from providing power capacity consists of the sum of the revenue received during each hour of the day over the course of the year, in accordance with equation 1:

(1) $r_{capres} = 365(10)(\sum_{i=1}^{24} f_i \, pcapres_i)$,

where r_{capres} represents the annual revenue from providing reserves capacity, f_i represents the fraction of the hour of the day that the vehicle is plugged into the grid at an outlet with appropriate V2G capability, and $pcapres_i$ represents the annual average price of one kilowatt of power capacity sold into the reserves market during that hour. The equation assumes that the amount of power capacity that the vehicle owner can sell into the market is limited to 10 kilowatts, due to residential power line limitations. Based on the data represented in Figure 2, we find that the annual revenue from the capacity payments amount to \$305.17.

The revenue from energy sales associated with providing reserves services depends on the price the vehicle owner is paid for each kilowatt-hour of energy fed into the grid, and how many kilowatt-hours he/she supplies over the course of the year. Kempton and Tomic (2005a) report that 20 calls, or dispatches, per year is a typical contractually specified maximum number of times a reserves supplier can be called upon to supply power to the grid. Therefore, we assume that the vehicle is used 20 times per year to feed power into the grid, with each dispatch lasting for 10 minutes. In addition, we assume that the amount of power the vehicle is called upon to feed power into the grid is 10 kW. We also assume that the probability of being dispatched is the same for each hour, and that the price the vehicle owner receives for supplying energy to the grid is the real time wholesale price that prevailed during that hour. The average real time wholesale location-based marginal price of energy in the Long Island Zone of the NYISO market was 5.96¢/kWh during 2010. Based on this statistic and the aforementioned assumptions, we can write the equation for the expected value of the energy sales portion of the revenue stream as follows:

(2) $r_{enres} = 20(10).0596(1/6) = \$1.99,$

where r_{enres} represents the energy sales revenue from providing reserves. Therefore, the total revenue stream from providing reserves services equals \$307.16. We now turn to calculating the costs of providing reserves services, once again following Kempton and Tomic (2005a).

The vehicle owner would incur three distinct types of cost in order to provide reserves services: battery cycling cost, the cost of the energy that was resold back into the grid at those times the vehicle was called upon to provide power, and the capital cost of the V2G equipment and household wiring upgrade that would be necessary to integrate the vehicle with the grid. Battery cycling costs arise in the context of reserves services because the battery must be discharged on those occasions when the vehicle is called upon to provide power to the grid. This cost can be written as:

(3) $c_d = \frac{c_{bat}}{L_{ET}},$

where c_d , c_{bat} and L_{ET} are the battery depletion cost, the cost of the battery, and the lifetime energy throughput of the battery, respectively. L_{ET} depends on how deeply the battery is cycled between discharge and subsequent recharge. Assuming that each dispatch lasts a total of ten minutes and that the power supplied on each dispatch is 10 kW, barely over one kilowatt-hour is drawn from the battery on each dispatch, and this would happen only 20 times per year. Since the depth-of-discharge is so trivial and happens so seldom in this case, we infer that the battery cycling cost of providing reserves services is negligible, so we ignore it.

An energy cost arises in the provision of reserves services because the vehicle owner must purchase the energy that the vehicle feeds into the grid on those rare occasions when it is dispatched. The cost of the energy dispatched, c_{endisp} , can be written as product of the cost of each kilowatt-hour of energy dispatched, c_{en} , and the amount of energy dispatched as part of the reserves contract, E_{disp}:

(4) $c_{endisp} = c_{en} E_{disp}$.

The relevant purchase price per kWh would be the retail price of electricity on Long Island, currently about 11¢/kWh. Under the assumption of a 17% round-trip conversion loss, the cost of each kilowatt-hour sold would be 13.2¢. On the assumption of 20 dispatches per year, each for 10 kW of power and lasting ten minutes, we can use equation 4 to calculate the cost of energy dispatched as being $4.40.

To annualize the upfront capital cost of the V2G equipment and wiring upgrade needed to integrate the vehicle with the ancillary services market, c_c , we multiply this cost by the standard capital cost recovery factor used in financial calculations:

(5) $c_{ac} = c_c \frac{d}{1-(1+d)^{-n}}$,

where c_{ac} , d , and n represent the annualized capital cost, the appropriate discount rate to convert future cash flows to current dollars, and the expected lifetime of the equipment, respectively. At the time of publication, Kempton and Tomic (2005a) estimate c_c to be $1900. The Consumer Price Index for Durable Goods for All Urban Consumers is the most appropriate index to convert the 2005 cost of the equipment upgrade to its 2010 cost, and this price index fell by 3.8% from 2005 to 2010. We therefore estimate that the up-front cost of upgrading the electronics of the vehicle to make it suitable for V2G, plus the cost of any necessary wiring and electronics upgrades within the household to be $1828.

In order for an assumed vehicle interface time of 50% between the hours of 09:00 to 15:00 to be attained, the vehicle would have to be plugged into an outlet with V2G capability for a substantial portion of the hours that it is parked at the owner's workplace, which would obviously require some electronics and wiring upgrading there. This would entail an additional incremental capital cost, and we assume that this cost would be borne by the vehicle owner, perhaps by a metered fee charged for the amount of time the vehicle is plugged into the workplace V2G outlet. There are no publicly available technical data that provide a guide on what this incremental cost would be, and we make a crude estimate that it would be one-half of the $1828 cost of upgrading both the residence and the car, or $914. We therefore estimate an all-inclusive value of $2742 for c_c .

We assume a 15 year useful life of the V2G electronics and wiring upgrades. In order to arrive at the appropriate discount rate, we use the current risk-free real interest rate on 15-year debt, then add a 4% risk premium. The most appropriate benchmark for the risk-free real rate of return is the interest rate on 15-year United States Treasury Inflation-Protected Securities (TIPS). At the time of this writing, an interpolation of data on the 10-year and 20-year TIPS yields indicates that the real interest rate on 15-year TIPS is approximately 1.05%. Adding the 4% risk premium gives us a discount rate of 5.05%. Equation 5 then yields an annualized capital cost of $265.06.

The total annual cost of providing reserves services, c , is the sum of the battery depletion cost, the cost of the energy dispatched, and the annualized capital cost:

(6) $c = c_d + c_{endisp} + c_{ac}$.

In this case, the total annual cost is $269.46, and the net profit, or revenue minus annual cost, is only $37.70, which very few EDV owners would likely find to be sufficient compensation for participating in the market for reserves services.

One important environmental benefit that is not captured in the foregoing financial calculation, however, is that using EDVs for reserves may substantially reduce emissions of nitrous oxide and other air pollutants by decreasing the need to run fossil fuel powered generators at partial capacity for reserves power sources (Sioshansi and Denholm 2009a). From an emissions standpoint, these generators operate more efficiently at full rated power than at partial capacity. On Long Island, which is plagued by ground-level ozone pollution on hot summer days, nitrous oxide emissions are of serious concern.

Sioshansi and Denholm (2009a), using data from the Electric Reliability Council of Texas, calculate a positive net economic benefit of anywhere between \$123 and \$224 per year per EDV used for reserves, depending on the extent of EDV penetration into the overall passenger vehicle fleet in Texas. One merit of their analysis is the incorporation of cost-savings for the system operator (and ultimately for end users of electricity) by being able to better optimize generator dispatch through control over the time of day that each vehicle is charged. However, they assume a capital cost of only \$300 to install the V2G electronics within the vehicle, and do not appear to take into consideration any capital costs incurred to upgrade the capacity of residential power lines.

Regulation Services

We now turn to using the vehicle for frequency regulation services as another potential profit-producer for the EDV owner. We employ, with some slight modifications, the analytical apparatus devised by Kempton and Tomic (2005a) and Tomic and Kempton (2007).

Like reserves services, the provision of regulation services generates two distinct revenue streams – one for the power capacity of the vehicle (larger revenue), and another for any energy sold into the grid when the vehicle is used for regulation up (smaller revenue). We assume a baseline power generation of zero under the regulation contract with the grid operator, which means that unless dispatched to feed power into the grid or draw energy from the grid, the vehicle would be neither charging nor discharging during hours that it is under contract to provide regulation. During regulation down the vehicle would go into a positive state of charging to draw energy off the grid, and we assume that the vehicle owner would pay the real time wholesale price of electricity for the energy drawn off the grid on these occasions. During regulation up, the vehicle would go into a discharging state to inject power into the grid, and we assume that the owner would be paid the real time wholesale price for energy fed into the grid at these times. We assume that it is just as likely that the vehicle would be dispatched for regulation up as regulation down, which assumes that the vehicle battery is never fully discharged or fully charged.

The fact that the vehicle would both feed energy into and draw energy from the grid under a regulation contract raises a series of complicating considerations. Energy sales revenue is generated whenever the vehicle engages in regulation up, and energy sold during these periods would have a round-trip conversion loss associated it (as it was purchased off the grid earlier). This means that there is a cost associated with the energy revenue derived from the regulation contract. The magnitudes of both the energy sales revenue and associated cost streams depend on the frequency and durations of the dispatches for regulation up. There is no energy sales revenue stream arising from regulation down since the vehicle does not feed electricity into the grid in these instances.

Kempton and Tomic (2005a) report a dearth of publicly available data on the amount of energy dispatched for regulation up by a typical generating station. The maximum potential dispatched energy is the product of the maximum power contracted for (P_{contr}) and the amount of time that the vehicle is contracted to provide regulation (t). Based on one day of high-frequency data obtained from CAISO, Kempton and Tomic (2005a) find a ratio for that day to be 0.08. We therefore accept this as a reasonable estimate for the "contract-to-dispatch ratio" (R_{d-c}), which is given by the following formula:

(7) $$R_{d-c} = \frac{E_{disp}}{P_{contr}\, t_{contr}},$$

where E_{disp} is the energy dispatched for regulation up under the regulation contract.

We now turn to the calculation of the revenue and cost streams of providing regulation. We assume that the vehicle is available the same fraction of hours of the day over the course of the year as we assumed in the reserves case. Figure 3 reports the relevant price data for the capacity payment under a regulation contract in the Eastern Zone of the NYISO (which encompasses the Long Island Zone) in 2010.

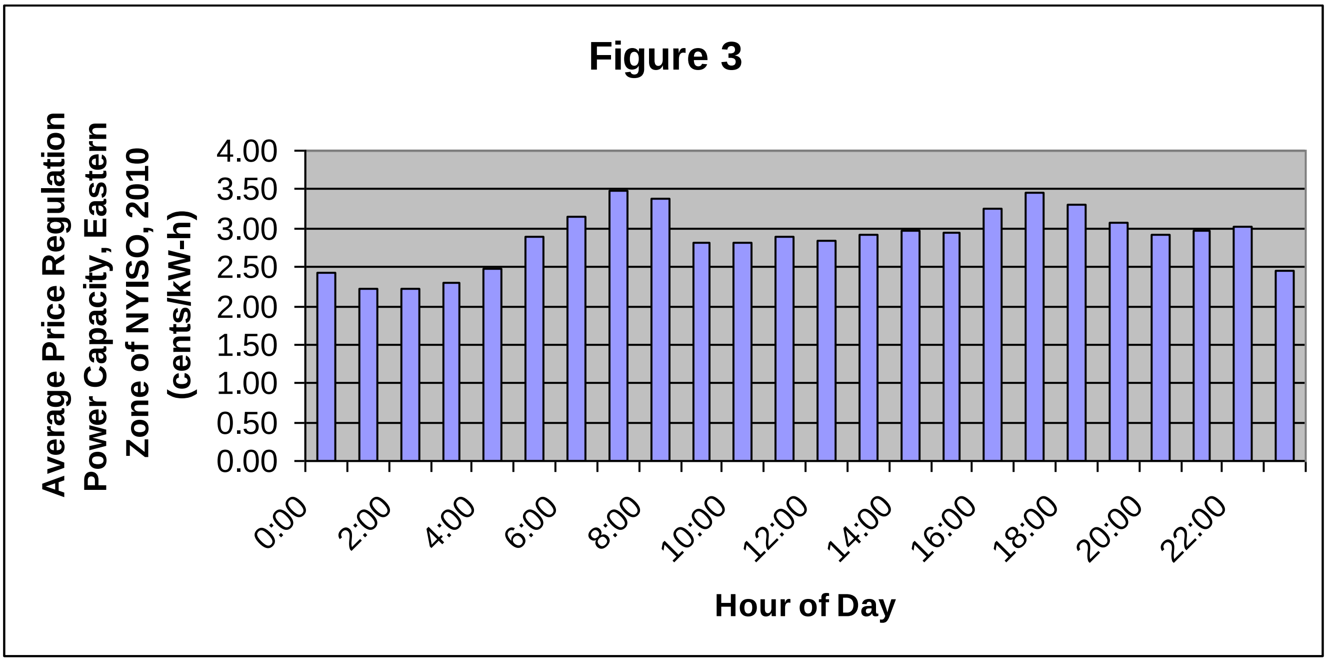

Figure 3. Energy price under regulation contract (data available upon request).

Based on the data in Figure 3, we use equation 8 to find the annual revenue from providing regulation power capacity:

(8) $r_{capreg} = 365(10)(\sum_{i=1}^{24} f_i \, pcapreg_i)$,

where $pcapreg_i$ represents the price per kW of regulation power capacity in hour *i*, and r_{capreg} is the annual revenue from the capacity component of the regulation contract. With the data and assumptions we have been working with, the annual capacity payment works out to be $1622.91. We now turn to the revenue stream from the energy sales arising from regulation up.

For simplicity, we assume that the probability that the vehicle will be dispatched for regulation up is the same for each hour of the day. We have been assuming that the vehicle is available more frequently at certain hours of the day, and so in order to calculate the energy sales revenue from regulation up, we need to know the annual average real time wholesale price of energy for each hour of the day. Based on the monthly reports published by NYISO, the closest we can come is to calculate the year-round average real time wholesale price of electricity over all hours in 2010, which was 6.13¢/kWh. We use this as an estimate for the energy sales revenue per kWh of energy sold into the grid during regulation up. Assuming the vehicle is plugged into the grid 15.95 hours each day on average, that it will be engaged in regulation up 8% of this time, that the average price the vehicle owner receives for energy sales is 6.13¢/kWh, and that ten kW of power are fed into the grid at each moment that the vehicle is dispatched, the annual revenue from energy sales from regulation (r_{enreg}) would be $285.50. We now turn to the cost of providing regulation services.

Regulation up entails energy cost in that the vehicle owner would not obtain for free the energy fed into the grid. Since we have been assuming an equality of probability of regulation up and regulation down at any moment in time, it is reasonable to view the energy injected into the grid during regulation up as having been obtained off the grid during regulation down, except for the 17% of the latter which is lost to round-trip conversion losses. This implies that 80% of the energy injected into the grid during regulation up cost the vehicle owner the real time wholesale price of 6.13¢/kWh since it was purchased during regulation down. The remaining 20%, which would have to be purchased in the regular retail market, would cost 11¢/kWh. However, the energy purchased in the retail market would also be subject to the 17% roundtrip conversion loss by the time it is re-injected into the grid. This entails that the actual cost per kWh of the energy fed into the grid, but obtained in the retail market is 120% of 11¢/kWh, or 13.2¢/kWh. The assumptions we have been making all along imply that 4657.4 kWh of energy will be fed into the grid each year during regulation up. The total cost of energy from regulation, c_{enreg} , is thus $351.36.

Exactly like reserves services, providing regulation services would entail an annualized capital cost (c_{ac}), because the owner of the vehicle would have to invest in additional equipment and electronics to provide V2G capability. We assume that the annualized capital cost of on-board electronics and residential power line upgrades is the same as it is for reserves, or $265.06. The total cost of providing regulation services (c_{reg}) is the sum of the energy and capital components:

(9) $c_{reg} = c_{enreg} + c_{ac}$,

or $616.42. There is no material battery depletion cost that would arise from providing regulation services, since the cycling of the battery from performing this function is extremely shallow. This leaves a net annual profit from providing regulation services of $1291.99.

The simple analysis undertaken thus far demonstrates a favorable economics of using an EDV with V2G capability for regulation services, but not for peak shaving and reserves. This analysis supports a previous analysis for the entire NYISO service area conducted by Alagappan, Cutter and Price (2009), which simulates the profitability of using a conventional energy storage device with 1 MWh of storage capacity and 2 MW of power capacity. They find that such a device has no value if used for peak shaving, minimal value when entered into the market for reserves services, but substantial value when used in the regulation market. In this section, we have focused on one EDV owner selling vehicle battery capacity into the market for frequency regulation services finding that the owner stands to make a profit in this scenario. In the next section, we will see that the outcome would be much different if a substantial number of EDV owners made bids into the market for regulation services, as the price of the service would be pushed down significantly.

Market Impact of Regulation Services by EDVs

The profitability calculations in the last section use historic price data that do not reflect what could happen to the price of regulation services if the number of EDVs in the regulation market becomes large enough to influence the price of regulation services. Such an eventuality would likely drive down the price of regulation power capacity, impacting the profitability of the calculations in the last section. In effect, the multitude of EDV owners would constitute what economists call a perfectly competitive component, and a potentially very large component, of the market for regulation services.

In a perfectly competitive day-ahead market for regulation services, each vehicle owner would set an asking price equal to the short-run marginal cost of providing the service during an hour of the next day. In a day-ahead market for regulation services during a certain hour of the next day, the system operator accepts bids from providers of the service starting with the lowest asking bid, and working up from there. Once the sum total of the power capacities of the accepted bids reaches the system operator's targeted level of regulation services for that hour, no further bids are accepted. The market-clearing price is then the asking price of the highest accepted bid, and all accepted bids are paid the market-clearing price, even though the majority of those bids have asking prices that are less than the market-clearing price. Therefore, a rational, profit-maximizing EDV owner bidding the vehicle's battery power capacity into the day-ahead market would want to make certain that the bid is accepted in all cases where the market-clearing price exceeds the short-run marginal cost of providing the service. Also, the owner would not want to have a bid accepted for any hour in which the market-clearing price is below the short-run marginal cost. Therefore, the vehicle owner would set an asking price equal to the short-run marginal cost of providing the service.

The only real marginal cost of providing regulation services is the cost of the energy conversion losses entailed when energy is taken off the grid, either during regulation down or as a retail purchase, then fed back into the grid under regulation up. As explained in the previous section, the conversion loss entails that 20% of the energy injected into the grid during regulation up has to be obtained in the retail electricity market at a cost of 13.2¢/kWh, after conversion losses. The expected cost of the energy conversion losses for providing one kW of regulation capacity for one hour would then be (1 kW-h)0.08(13.2¢//kW)0.2=0.21¢. This marginal cost figure is certainly below that of any conventional generator providing regulation services. It is also the price that a rational, profit-maximizing vehicle owner would bid to participate in the market for regulation services. The reader should note that this marginal cost falls considerably below the current annual average hourly market prices of regulation capacity reported in Figure 3.

We now turn to where we should expect the market price of regulation capacity to end up if a substantial number of EDV owners were offering their capacity into the day-ahead market for regulation services. As long as the total regulation capacity bid into the market by the fleet of EDV owners falls short of the system operator's projected need for regulation, the market price for that hour would end-up above 0.21¢/kW-h, assuming that no conventional generator bidding into the regulation market asks a price at or below 0.21¢/kW-h. One should recall that the market-clearing price, which is the price that each accepted bid receives, equals the highest asking price that system operator accepts. In this event each EDV owner would make money, on the margin and ignoring the fixed capital cost that he/she incurred in the past, on the contract for that hour as the market-clearing price would settle above 0.21¢/kW-h.

However, once the fleet of EDVs had grown sufficiently large that the regulation capacity of the vehicles was sufficient to cover the system operator's estimated need for regulation capacity, the market-clearing price would be effectively capped at 0.21¢/kW-h. That is, the regulation capacity bid into the market by the vehicle owners would more than cover the needed quantity of regulation services, and no bids above 0.21¢/kW-h would be accepted. This could happen relatively quickly if EDVs are allowed to participate in the regulation market, since the total regulation requirements in the NYISO service region amount to only 1%-1.5% of the average load there. Once this level of market saturation by EDVs is reached, a vehicle owner could, at best, breakeven on the margin by offering the vehicle into the day-ahead market for regulation services, and would lose money once the annualized capital cost is taken into consideration. In effect, all the economic value from using the vehicles for regulation services would flow to end-users of electricity, who would now end-up paying a lower price for regulation services, leaving vehicle owners losing $265.06 each in annualized capital costs per year. Moreover, the gains to final users would be small, as the cost of regulation services constitutes only about 1% of their total electricity bills. This analysis supports other conclusions that have also anticipated that the market for regulation services would be saturated on short order if EDVs participated in the market (Andersson et al. 2010; Peterson, Whitacre, and Apt 2010; Sioshansi and Denholm 2010).

Once the fleet of EDVs with V2G capability becomes substantial, a competitive, uncoordinated market mechanism for regulation services will not provide the vehicle owners with an incentive to provide the service. No rational vehicle owner would incur the up-front capital cost for V2G technology and a household power line upgrade to integrate the vehicle with the grid, when the subsequent annual net cash flows would be zero. A system other than a competitive market would be necessary to incentivize vehicle owners to provide regulation services. Perhaps the electricity regulator or the system operator could impose a surcharge on all end users of electricity, with the proceeds transferred to EDV owners who commit their vehicles to providing regulation services for a certain number of hours each month. After all, the end users would be already benefiting from the significantly reduced cost of regulation services, and the surcharge would be a mechanism for sharing the gains from integrating the vehicles into the regulation services market with the EDV owners.

Another viable alternative would be for the regulatory body or system operator to grant an exclusive license to one aggregator, perhaps a cooperative body controlled by EDV owners within the system operator's geographical boundaries, to purchase the regulation services of the vehicles, then resell these services into the regulation market. It is worth noting that other researchers, such as Kempton and Tomic (2005b) and Quinn, Zimmerle and Bradley (2010) also advocate the use of an aggregator, but for reasons having to do with coordination of the services, not because of the incentive problem discussed here. Also, Guille and Gross (2009) have created a fairly detailed framework that would allow the aggregator to interface with the power system operator. An aggregator scheme, unlike a competitive market arrangement, would provide the vehicles owners with a degree of market power, thereby preventing price from falling all the way to the marginal cost of providing regulation services by these vehicles.

Summary of Findings and Closing Remark

The economics of using an EDV for peak shaving and providing reserves services in the Long Island Zone of the NYISO are unfavorable. However, allowing EDV owners to participate in the wholesale market for frequency regulation services offers the first movers among them an opportunity to receive a substantial profit stream that would help to offset the relatively high purchase price of an EDV compared to a conventional automobile. Their participation in the market would also help to reduce end-user electricity bills by a small amount. However, in order to realize these benefits, care must be exercised in crafting the institutional arrangement that integrates the vehicles in the regulation services market, as the wrong institutional arrangement will strip the vehicle owners of a financial incentive to participate.

Without a planned institutional arrangement, the early movers among EDV owners to offer their battery and vehicle electronics capacities into the regulation market would be the primary beneficiaries among EDV owners. The market for regulation services in the NYISO service area would become saturated in fairly short order as EDVs began to supply regulation services. However, the prospect of the erection of wind farms off the shore of Long Island holds the possibility of greater demand for regulation services, and some forestalling of the date of market saturation as wind power is an intermittent and unpredictable source of electricity. Other researchers, such as Kempton and Tomic (2005b) and Divya and Ostergaard (2009), have explored how the economics of regulation services by EDVs and of wind farming mutually complement each other.

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