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A conceptual framework for the *vehicle-to-grid* (*V2G*) implementation

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Abstract

The paper focuses on presenting a proposed framework to effectively integrate the aggregated battery vehicles into the grid as distributed energy resources to act as controllable loads to levelize the demand on the system during off-peak conditions and as a generation/storage device during the day to provide capacity and energy services to the grid. The paper also presents practical approaches for two key implementation steps – computer/communication/control network and incentive program.

Keywords: Power systems; Electric vehicles; Smart grid

Article Outline

1. Introduction

There are growing concerns around the world about energy independence and global warming issues. In the USA, energy independence is a major political issue due to the fact that the nation imports two-thirds of the oil it consumes – virtually, all the fuel consumed for transportation purposes.[1] The strong dependence on foreign sources to satisfy this so-called "oil addiction", together with the growing awareness of global warming impacts that CO_2 emissions produce, are key drivers for the development of new transportation technologies. Such technologies aim to drastically reduce the need for oil by making the vehicles more fuel-efficient and by turning to alternate sources of energy. In particular, the development of the battery vehicles or *BV*s in the form of either plug-in hybrid vehicles (*PHEV*s) or all-electric vehicles (*EV*s) is directly addressing these issues. We make no distinctions between *EV*s and *PHEV*s in the remainder of the paper. The common characteristic of *EV*s and *PHEV*s is that they require a battery, which is the source of all or part of the energy required for propulsion. Car manufacturers have heeded the call for the generation of new vehicles and are currently designing new products. The tremendous success of the *Toyota Prius* has been a motivating factor for car manufacturers in pushing out the development of *BV*s. While *Chevrolet* is scheduled to commercialize its *Volt* in 2010, *Toyota* announced that it plans to launch an *EV* by 2012 and offer 10 new hybrids in the early 2010s. The Obama administration has identified a 2.4 billion dollars funding for the development of *BV*s as part of the stimulus package in the American Recovery and Reinvestment Act (ARRA) 2009. Because of all the various activities underway, we can expect a massive deployment of *BV*s over the next few years. We explicitly assume in the present work that we are at some point in time in the future at which there is a deep penetration of *BV*s. Such an explosion in growth creates both a new load class for charging the batteries and new opportunities for the effective integration of *BV*s into today's grid. *FERC* recently emphasized the urgent need to accomplish this integration for the future health of the system.[2]

Given the nature and physical characteristics of *BV*s, their integration into the grid is performed at the distribution voltage level. Such an interconnection allows each *BV* to be plugged into the grid to get the energy to charge up the battery. The *BV*s, when aggregated in sizeable numbers, constitute a new load that the electricity system must supply. However, a *BV* can be much more than just a simple load given that bi-directional power transfers are possible once the interconnection is implemented. Indeed, the integration allows the deployment of *BV*s as a generation resource as well as a storage device for certain periods of time when such deployment aids the system operator to maintain reliable operations in a more economic manner. We refer to the aggregated *BV*s as a generation/storage device in this case. The entire concept of using the *BV*s as a distributed resource – load and generation/storage device – by their integration into the grid is known as the *vehicle-to-grid* (*V2G*). Under this concept, the *BV*s become active players in grid operations and play an important role in improving the reliability, economics and environmental attributes of system operations. Such benefits include the provision of capacity- and energy-based ancillary services, the reduction of the need for peakers and load levelization. However, *V2G* is still in the conceptual stages and is waiting for its implementation – a daunting challenge particularly for deep penetration of *BV*s. In this paper, we propose a practically oriented conceptual framework to move from concept to implementation. The framework is based on the extensive use of aggregation to overcome the small storage capability/capacity limitation of a *BV* battery. The battery of a vehicle is a very small resource whose impact on the grid is negligible. The construction of the framework exploits the deployment and physical characteristics of *BV*s and takes full advantage of the vehicles, while they are parked by harnessing their batteries to make beneficial contributions to the grid as a load and generation/storage device. The framework design is comprehensive as it explicitly recognizes the entire range of roles that the aggregated *BV*s can play. As a load in the charging phase during the off-peak conditions at night, the *BV* aggregation may be deployed to levelize the load, thereby contributing to lowering the need for *down regulation* service during those periods (Blumsack et al., 2008). As a resource during the day, when the *BV*s are parked, the *BV* aggregation can provide *up* and *down regulation* service, as well as, peak shaving energy. In this way, the *BV*s act as both a generation source and a storage device. The Aggregator who collects the *BV*s to create a group to act as the distributed energy resource (*DER*) is the critical entity to make the *V2G* concept implementable. The Aggregator also provides interface with the independent system operator or regional transmission organization, i.e., the *ISO*/*RTO*, whose responsibility is to operate and control the bulk power system, and with the energy service providers (*ESP*s) who provide the electricity supply to customers through the distribution grid. Implementational steps for two main components of the framework are also detailed in the paper. The scope of the paper encompasses the development of an analytical framework and its application to the investigation of various issues and policies in the actual implementation of *V2G*. The objective is to provide a conceptual construct to serve as a tool for designing and implementing the platform for the effective integration into the grid of the *BV*s that are forecasted to become in wide use over the next few years.

For the power industry, the ability of the current system to accommodate the additional load of the *BV*s poses a challenge. A study showed that, in 2020, with a 25% penetration in 13 US regions, 160 new power plants will be required if every *BV* owner plugs in the vehicle in the early evening – around 5 p.m. – when electric demand is still near the daily peak.[3] However, with smart-grid technology (Amin and Wollenberg, 2005), utilities may stagger charging times, offer consumers lower rates for off-peak electricity and can virtually eliminate the need for new power plants. The situation may even be better in some regions. For example, a study which considers the integration into California grid of 4 million *PHEV*s – a 25% penetration – shows that the load of charging this number of vehicles can be accommodated by the current power system without requiring the installation of new generation sources (Sanna, 2005). In fact, the small change in the total demand with all the *PHEV*s integrated into the grid can be well handled by the existing installed capacity. We provide the plot of the daily state-side load with and without *PHEV*s in Fig. 1. In California, in fact, the *BV*s can help the system to overcome the problems with the low loads at night by better utilizing base-loaded units, such as nuclear generators, that can maintain a continuous steady output even during the off-peak periods by charging the *BV*s.

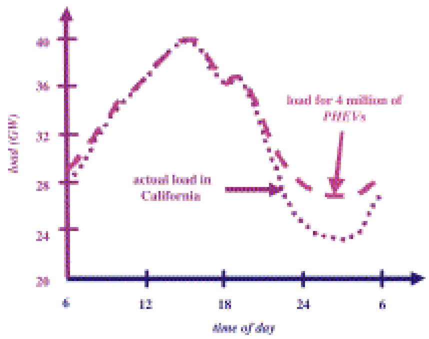

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Fig. 1. The California daily load with and without *PHEV*s for a typical summer day.

The paper contains five additional sections. In Section 2, we discuss the characteristics of the *BV*s. In Section 3, we present the reasons for and nature of the aggregation of the *BV*s and discuss the possible contributions the *BV* aggregation can make as both a load and a generation/storage device. We devote Section 4 to the design of the framework for the implementation of *V2G* and discuss in Section 5 the two main implementational challenges – the design of a communication system and of an incentive program. We conclude with some remarks and directions for future steps in Section 6.

2. *BV*s: salient characteristics

*BV*s have two fundamental characteristics of interest to this work – one is that the *BV*s are vehicles and the other is that they have batteries on board that can both generate and store electricity.

As vehicles, *BV*s are not always stationary and, therefore, may be dispersed over a region at any point in time. In a moving state, *BV*s may be used for commuting purposes or, possibly for longer trips – if the battery capacity is large or if the *BV* is a *PHEV*. Our focus in this study is on the use of *BV*s for daily commuting purposes. A study for *ABC News* in 2005 showed that the roundtrip average commuting distance in the US is 32 miles – about 50 km – and the average commuting time is around 52 min with a very large variability: commuting times can be twice as large as the average under certain conditions.[4] Survey data on the commuting patterns of US drivers nationwide indicate that 60% of the commuters drive a distance under 50 miles–80 km. The plot in Fig. 2 represents the cumulative percentage of vehicles as a function of the one-way commuting distance (Sanna, 2005).

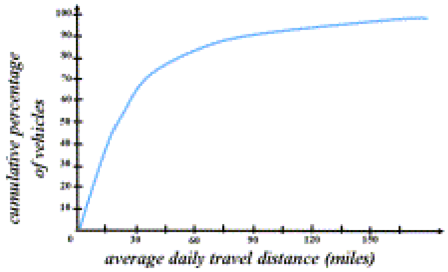

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Fig. 2. Cumulative percentage of vehicles as a function of the nation-wide one-way commuting distance.

For the *BV*s used for commuting, we can view, therefore, that the vehicles are idle an average of 22 h a day. We note that as the commuting distance is smaller than the potential range of the *BV*s, not all the energy in the batteries is consumed by the commute. We may see each *BV* as a potential source of both energy and available capacity that can be harnessed by the grid in addition to supplying the load of the *BV* to charge up the battery.

We discuss next the battery. The typical range for commercial[5] *BV* battery[6] storage *C* – also called storage capability – is from 1 to 60 kWh. Batteries have very fast response capabilities, of the order of *milliseconds* to reach their maximum output and can usually be fully recharged in 5 h or less (Chan and Chau, 2001). Thus, the battery output is usually in the 0.2–6 kW range.

In addition to the storage capacity, there are some other aspects of interest in characterizing the batteries. A critically important one is the state of charge (*s.o.c.*) of the batteries. It is defined as the ratio of the energy stored in a battery to the capacity of the battery. It varies from 0 when the battery is fully discharged to 1 – often expressed in percentages as a variation from 0% to 100% – when the battery is fully charged and provides a measure of how much energy is stored in the battery. The *s.o.c.* typically decreases when energy is withdrawn from the battery and increases when energy is absorbed by the battery. Thus, for a day during which the *BV* owner goes to work in the morning, parks the *BV*, goes back home in the late afternoon and then plugs the *BV* for charging during the night, the *s.o.c.* will evolve along a pattern illustrated in Fig. 3.

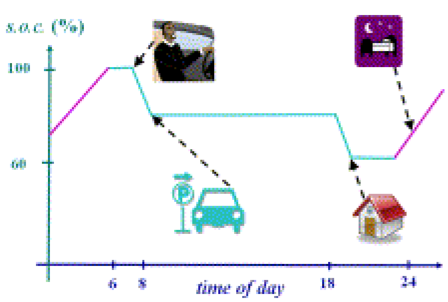

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Fig. 3. Evolution of the *s.o.c.* of a *BV* for a typical day.

Batteries release energy more easily when their *s.o.c.* is high or more exactly above a tolerance level. We stipulate 60% to be the tolerance level in this work. When the *s.o.c.* is lower than 60%, a more appropriate utilization of this battery is for energy absorption. Also, overall battery performance for either absorption or release is much higher in a band around this tolerance level (Yamane et al., 2002). The width of this band is not well understood and so is still a topic of research. If the battery releases energy, then the *BV* acts as a supply-side resource. If it absorbs energy, the *BV* acts as a demand-side resource. We can view the battery to represent supply- and demand-side resources as a function of the *s.o.c*. The diagram in Fig. 4 summarizes this information.

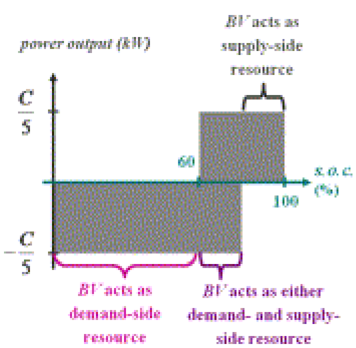

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Fig. 4. The *s.o.c.* determines the functioning of the battery.

The frequent switching of the *s.o.c.* may cause a decrease in battery storage capability which is defined as the battery degradation. We use the value of the *s.o.c.* metric as the decision determinant to optimize the performance and also to decrease the battery degradation. For example, the charger of a *BV* battery stops drawing current when the *s.o.c.* reaches 85% or 90% level. If such appropriate rules are used the battery life can be quite long. Some firms – *A123Systems* for example – claim that the manufacturing of batteries with 10-year lifetimes is currently feasible.

Battery degradation is also a function of the depth of the discharge and the frequency of the fluctuations. In a study presenting the results of a *V2G* test for frequency regulation, the investigators noticed that, at the end of a one week test, the capacity of the tested battery had increased (Brooks, 2002). Their explanation is based on the fact that very small amounts of energy were concerned and that the frequency of the variations was high.

In concept, once plugged into the grid, *BV* batteries may be used as *DER*s. However, the maximum capacity of a typical *BV* battery is rather small. Such an output cannot make any impact on the grid scale on its own. A *BV* appears simply as *noise* in the power system at the grid level. For the *BV*s to be a useful resource, a degree of aggregation is required to bring about a size that can impact the grid. We devote the next section to discussing the nature and the role of aggregation in *BV*s.

3. Contributions of the *BV* aggregations

The battery storage of an individual *BV* is too small to impact the grid in any meaningful manner. An effective approach to deal with the negligibly small impact of a single *BV* is to group together a large number of *BV*s – from thousands to hundreds of thousands. The aggregation, then, can impact the grid both as a load and a generation/storage device.

The basic idea behind such aggregation is the consolidation of the *BV*s, so that together they represent a load or a resource of a size appropriate to exploit economic efficiencies in electricity markets. The Aggregator is a new player whose role is to collect the *BV*s by attracting and retaining them so as to result in a MW capacity that can impact beneficially the grid. The size of the aggregation is indeed the key to ensuring its effective role. In terms of load, an aggregation of *BV*s represents the total capacity of the batteries, an amount in MWs that constitutes a significant size and allows each *BV* to benefit from the buying power of a large industrial/commercial customer. There are additional economic benefits that accrue as a result of the economies of scale. The aggregated collection behaves as a single decision maker that can undertake transactions with considerably lower transaction costs than would be incurred by the individual *BV* owners. So, the aggregated entity can make purchases – be it electricity, batteries or other services – more economically than the individual *BV* owners can and can pass on the savings to each *BV* owner. As a resource, the aggregated *BV*s constitute a significant capacity that may beneficially impact the operations of an *ISO*/*RTO*. We may view the *BV* aggregation as a *DER*. The *ISO*/*RTO* deals directly with the Aggregator, who sells the aggregated capacity and energy services that the collection of *BV*s can provide. The Aggregator's role is to effectively collect the *DER*s into a single entity that can act either as a generation/storage device capable of supplying capacity and energy services needed by the grid or as a controllable load to be connected to the *ESP* to be charged in a way so as to be the most beneficial to the grid. It is the role of the Aggregator to determine which *BV*s to select to join the aggregation and to determine the optimal deployment of the aggregation. A single aggregation may function either as a controllable load or as a resource, as depicted in Fig. 5. We discuss first the *BV* aggregation utilization as a controllable load and then as a generation/storage device.

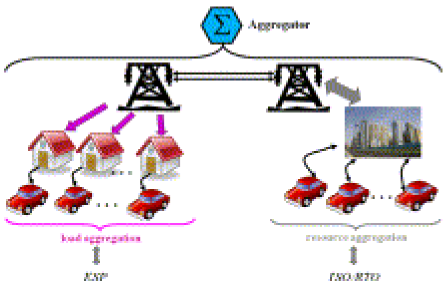

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Fig. 5. The *BV* aggregation may act as a controllable load or as a generation/storage device.

The charging of the *BV*s introduces a new load into the system. For every *ISO*/*RTO*, the load has a typical daily shape formed of on-peak and off-peak periods. Both the peak loads and the load shapes depend on seasonal factors – most of the US is summer peaking with the air conditioning loads constituting an important part of the total demand. We use the load in the winter in *New England ISO* to provide an example of the daily load shape. Fig. 6 provides the hourly load for Thursday, February 21, 2008.

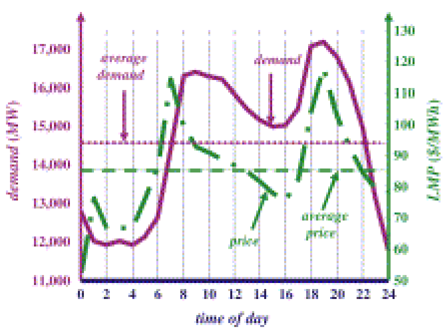

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Fig. 6. Load and price for a typical winter day for *NEISO*.

The causal factors of the two daily peaks at around 8 a.m. and 7 p.m. are different. The morning peak is mainly caused by industrial and commercial customers while the evening peak is associated with the behavior of residential customers, who return to their homes and turn on their various appliances. The hourly electricity prices track the loads rather closely. We provide a plot in Fig. 6 of the locational marginal prices[7] (*LMP*s) realized at a node called *HC.AYER 115* in the *New England ISO* system on February 21, 2008. We note that, at this location, it makes ample sense for the *BV*s to be charged between 0 a.m. and 6 a.m., the low-load period, so as to benefit from the low prices at that node.

A *BV* aggregation may play a very useful role as a load when the total load created by the aggregation is of sufficient size. As an example, we may consider an aggregation of 12,500 *BV*s. If we take the average *BV* battery storage capacity to be 20 kWh and a 5-h average charging time, the aggregation represents a 50-MW load, an amount that has an impact on a system during off-peak conditions. A key objective of deploying the *BV* aggregation as a load is to levelize the loads during the charging period. The controllability of the load allows the Aggregator to do the charging of the *BV* batteries in a way so as to ride out the load fluctuations during the low-load periods. Load levelization requires careful management of the charging periods of the *BV*s and requires explicit consideration of the *s.o.c.* of each battery in the aggregation. Without aggregation and without explicit centrally dispatched control to manage the charging periods, the demand by the *BV*s increases and as a result of lack of levelization so do the requirements for regulation service. Therefore, we conclude that the load levelization control results in reduced energy and reserve requirements compared to the case of no such control. Such load levelization is a major contribution to the *ISO*/*RTO*'s operations, since the dispatch for a flat load is far less complex than for a fluctuating load. We conceptually illustrate in Fig. 7 the impacts of the aggregated *BV*s into a controllable load on a system whose demand is fluctuating. As a load, therefore, the aggregated *BV*s can help system operations not only by being a useful sink but also by levelizing the load during off-peak period. The load levelization considerably simplifies system operations since the forecasting of the flattened load is much easier and the down regulation requests from generators are avoided, because the load levelization control takes care of such need.

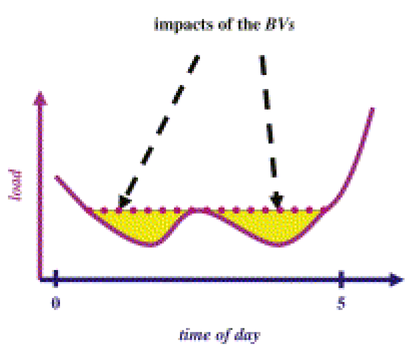

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Fig. 7. The charging of the *BV*s can be done so as to levelize the load during the off-peak period.

The *BV* aggregation can act as a very effective resource by helping the operator to supply both capacity and energy services to the grid. To allow the operator to ensure that the supply–demand equilibrium is maintained around the clock, the *BV* aggregation may be used for frequency regulation to control frequency fluctuations[8] that are caused by supply–demand imbalances. The shape of the regulation requirements varies markedly from the on-peak to the off-peak periods. We define *regulation down* as the absorption of power and *regulation up* as the provision of power. A battery may provide *regulation up* or *regulation down* service as a function of its *s.o.c*. Depending on its value for each *BV* in the aggregation, the collection may be deployed for either *regulation up* or *regulation down* at a point in time. Resources that provide regulation services are paid for the capacity they offer. We show in Fig. 8 a representative example of the shape of regulation services required by a large *ISO*/*RTO* together with the prices for their services. We point out the acute need for *regulation down* service during the night, whereas, during the day, there are needs for both *regulation up* and *regulation down* services. We also note that the variability in the prices is very pronounced in the off-peak periods and less so in the peak hours. We wish to emphasize that the prices we provide here have an illustrative purpose. The price of regulation service may be different in recent months as it depends on the state of electricity markets and on the period of the year we consider.

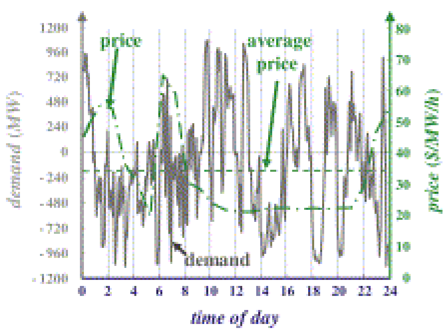

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Fig. 8. Required regulation service and prices for *PJM* for June 6, 2006.

The high prices for night-time regulation are representative of the situation in other *ISO*/*RTO*s. For example, Fig. 9 shows that, for the *California ISO*, the price of regulation at 3 a.m. was higher than 250 $/MW/h eleven times in April 2006, nearly one out of three nights.[9]

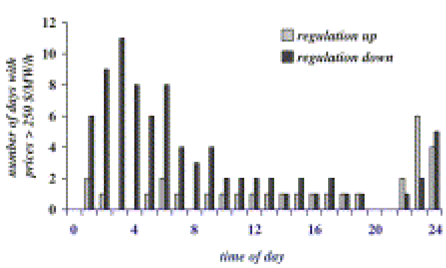

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Fig. 9. Number of days with prices higher than 250 $/MW/h for the regulation service for *CAISO* in April 2006.

Indeed, compliance with the unit commitment schedules becomes difficult in the low-load conditions during the off-peak periods. While the operator may not wish to turn units off, in some cases, there may be no choice. Therefore, these situations lead to the much higher prices for the *regulation down* service during the off-peak periods, particularly when compared to those for the *regulation up* and the *regulation down* services in the peak periods. The addition of the load of the aggregated *BV*s for charging during the night not only increases the load but also, consequently, decreases the need for regulation services. As a result, the units in the resource mix will not need to be turned off during the night and will be ready for the load pick-up in the morning.

In addition to lowering off-peak regulation needs, the aggregated *BV*s may be also deployed to provide day-time regulation service to the grid given the fast response capabilities of the *BV* batteries, of the order of *milliseconds*. Typically, such service is provided by plants with short response times, of the order of *minutes*. These plants can be controlled to increase or lower their outputs. The batteries of the *BV* aggregation can either absorb or discharge energy depending on the *s.o.c.* of each individual battery, but can do so with a much faster response time than conventional units. The deployment of aggregated *BV*s for such regulation service may not necessarily involve the supply of energy but simply the use of the capacity they provide.

While the use of *BV*s to meet the base load has previously been questioned (Kempton and Tomic, 2005), the aggregated *BV*s may be used to provide reserves to the grid. A sizeable aggregation of *BV*s can provide considerable support to a system operator by allowing the delay of the start-up of the cycling and peaking units. The operator, to ensure the ability of the generation system to meet the load during peak conditions, performs start-up of the needed units some hours ahead of time to ensure that the unit physical constraints are not violated. The fast response capabilities of the *BV* batteries allow the *BV* aggregation to provide capacity and energy nearly instantaneously. Consequently, they can offer insurance to the system that the load can be met. The *ISO*/*RTO* can, therefore, delay or even avoid the start-up of the cycling and peaking units because of the reliance on the aggregated *BV*s. We illustrate this notion in Fig. 10 for a system for which the *BV* aggregation may introduce a delay of *several hours* in the start-up of the cycling units. We indicate that this capacity-based service need not involve the provision of load shaving service. The *BV*s receive additional payment whenever they also provide energy for load shaving purposes. In case the energy is actually required, the aggregated *BV*s sell, through the Aggregator, some part of the energy stored in their batteries. In this case, the aggregated *BV*s also play the additional role of an energy resource.

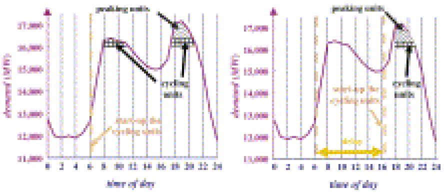 [Full-size image](45K)

Fig. 10. *BV*s provide support service to allow the *ISO*/*RTO* to delay the start-up of the cycling units by several hours.

Aggregated *BV*s have the potential to play a very important role in improving system operations both on the demand- and the supply-side. However, for the concept to be successful, a careful implementation is required. We next describe the necessary components for such an implementation.

4. Proposed framework

Central to the *V2G* concept is the integration of the *BV* aggregation into the grid so that the *BV*s can make beneficial contributions both as a controllable load and as a generation/storage device. However, the challenge of going from the *V2G* concept to the actual integration of *BV*s into the grid is immense. A key need is to develop a conceptual construct or framework whose implementation can bring to the realization of the *V2G* vision. We devote this section to describe the framework we propose for this purpose.

The framework is built taking fully into account the physical characteristics of the *BV* batteries and the deployment of the *BV*s. In this way, we can effectively harness the contribution the *BV* aggregation can make as either a controllable load or a generation/storage device. Specifically, we track each *BV* battery *s.o.c.* and use it as the determinant for the role each *BV* can play once plugged into the grid. The Aggregator becomes the essential enabler in making the *V2G* concept realizable in practical terms. The Aggregator we describe here provides the aggregation function for the *BV*s as a resource and as a load. This aggregation function may be provided by a new player or by the *ESP*. The Aggregator interfaces with the *BV* owners, the *ISO*/*RTO* and the *ESP*s serving the residences of the *BV* owners. We display in Fig. 11 the interrelationships among these entities.

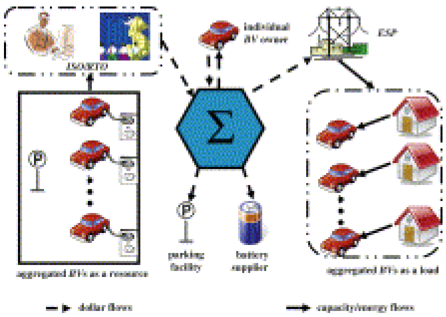

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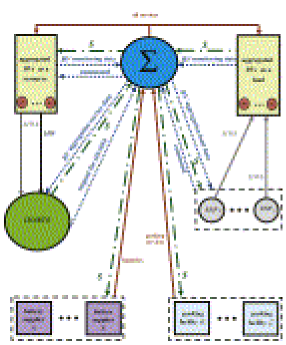
Fig. 11. The incorporation of the Aggregator into the *V2G* concept.

The framework makes effective use of the *BV* aggregation but leaves the identity of each *BV* unchanged. In the framework, we use two distinct modules for the *BV* aggregation as a load and as a generation/storage device. The Aggregator module is at the center of the construct and the *ISO*/*RTO* and the *ESP*s, with which the Aggregator interfaces, are represented by their separate modules. The flows in the framework represent the interrelationships between the players. The flows may be commodities, services, information or dollars. Conceptually, we may view the framework to consist of a physical layer, where the flows are MW, MWh, battery service and parking service, which is accompanied by a separate layer with information flows to reflect control commands, monitoring data, billing information and any other communication that may be necessary among the various players.

We next examine in detail the capability of the components and their interrelationships to effectively represent all the elements of the *V2G* concept. We use the schematic of the proposed framework shown in Fig. 12 to aid us in this examination. The *BV* aggregation as load receives the electricity supply for charging the batteries from the *ESP*s that serve the residences of the *BV* owners. This physical commodity flow is indicated by the MWh links in Fig. 12. Similarly, the *BV* aggregation as a generation/storage device supplies energy and capacity services to the *ISO*/*RTO* through the MWh and MW links in Fig. 12. These load and resource services are coordinated through the Aggregator, the central entity that interfaces with the *ESP*s and the *ISO*/*RTO*. In addition, the Aggregator provides the aggregated *BV*s the batteries and their maintenance as well as the parking services. The Aggregator makes use of its large purchasing power to acquisition those services directly from the battery manufacturers and parking lot owners, respectively, and provides them to the *BV*s as part of the collection of services that allow the *BV*s to be integrated into the grid. Conceptually, we can view all these services as flowing on the physical layer of the framework. However, it is the information layer provided by the computer/communication/control infrastructure that enables the needed monitoring, management of command and control signals and provision of the various services together with the flow of the payments for the services. It is this layer that makes the aggregations function appropriately while simultaneously allowing the Aggregator to deal with each individual *BV* to effectuate the needed controls and deliver the services. The Aggregator uses the direct control of each individual *BV* to assess the need for various services and the capability to provide the MW and

MWh services. For the load aggregation of *BV*s, the Aggregator has bi-directional communications with the *ESP*s to specify the information needed for the charging of the batteries and for the requirements of load levelization services. The corresponding signals to the *BV*s are transmitted through the network. In the case of the resource aggregation of *BV*s, the Aggregator uses the network to convey the needs of the *ISO*/*RTO* for capacity and energy services, to identify the subset of *BV*s in the aggregation that can provide them and to measure the contribution of each *BV* in the subset. The monitoring, control and information flows are indicated by dotted lines in Fig. 12. Conceptually, we also view that the dollar flows to pay for the various services are accommodated by the information layer. The computers that are integral part of the computer/communication/control system keep track of the set of services that *BV*s receive from the Aggregator together with the relevant discounts, and also the set of services provided by the *BV*s while parked and interconnected to the grid. The dollar flows are indicated through separate lines in Fig. 12. The diagram is shown by collapsing the physical and information flows together to emphasize the extensive interactions among the various components of the framework.



Full-size image (94K)

Fig. 12. The proposed *V2G* implementation framework.

The proposed framework is comprehensive as it includes the necessary modules and interactions needed for the *V2G* concept to be implemented. The framework constitutes a useful construct because it makes clear the specific flows that need to be implemented to bring *V2G* to reality.

5. Steps toward the framework implementation

The implementation of the proposed framework poses a good number of challenges. A critically important prerequisite is the construction of the information layer: the establishment of the infrastructural computer/communication/control network for the integration of the aggregated *BV*s into the grid. An equally important element whose implementation is essential is a scheme for the Aggregator to attract and retain *BV* owners with the appropriate incentives incorporated.

We devote this section to the discussion of the approaches we propose to tackle these two key implementational issues.

We emphasize in the discussion of the proposed framework the essential role of the information layer in facilitating the flows of information required by the various entities participating in the bringing to fruition of the *V2G* concept. Specifically, the computer/communication/control network needs to have the capability to make the required informational transfers between the Aggregator and each *BV* and between the Aggregator and the *ISO*/*RTO* and the *ESP*s. These transfers are bi-directional and are required around the clock. The Aggregator must continually monitor the status of each *BV*, collect the data for the services provided to the *BV*s and the *ISO*/*RTO*, keep track of the services provided by the *BV*s and maintain the data required on the battery purchase and maintenance and on the parking services. In addition, the network must provide the appropriate interfaces for metering the electrical flows to and from each individual *BV*, for storing all the data collected including those for billing purposes, and for transmitting the control signals to the *BV*s from the *ISO*/*RTO* and the *ESP*s to drive the batteries to perform the desired actions.

The computer/communication/control infrastructural network must comprise several subnetworks which need to be seamlessly integrated together to meet the need outlined above. For example, a subnetwork is required at each location where the *BV*s are plugged into the grid to transmit data over short distances. On the other hand, the transmission of data between the parking lots and the Aggregator involves longer distances. The computer signals sent by the *ISO*/*RTO* which need to be broadcasted to each *BV* in the aggregation have very fast response requirements as do the signals for load levelization control emanating from the *ESP*s. Given the diversity of applications, the computer/communication/control network must meet some key basic requirements, which include, at a minimum, the following:

• *low cost*: the additional costs of the installation and maintenance of the communication network for *BV* integration must be negligibly small compared to the price of the *BV;*

• *fast response*: the network must accommodate the speedy delivery of the signals sent to the *BV*s;

• *extensive range*: the network must be able to economically integrate each *BV* in a parking lot;

• *flexibility and extendability*: the network must provide the capability to add more *BV*s willing to participate in the aggregation without incurring major modifications or retrofits;

• *high reliability*: the reliability of the communication network is critical for the Aggregator to effectively carry out its responsibilities; and,

• *security*: the cyber security of the communication network must be assured so as to prevent its use in cyber-attacks.

In addition to these *de minimus* requirements, the computer/communication/control network must have the capability to transmit data on a very frequent periodic basis to perform the range of services required for the *BV* integration. We provide in Table 1 a summary of the type and nature of the information that must pass through the network. The capability to speedily and accurately transmit control signals to each individual *BV* to request that the appropriate action be taken for *up* and *down regulation* and for the provision of energy by the battery while the *BV* is parked and plugged in during the day imposes rather rigorous requirements. The same is true for handling the control signals to do the charging in line with the load levelization needs of the *ESP*s during off-peak conditions at night.

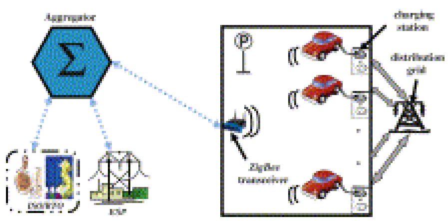
Table 1.

Nature of data that are transmitted from each *BV* to the Aggregator.

Data	**Nature**	**Comments**
ID	Unique alphanumeric information characterizing the *BV*	The key to retrieve the specific characteristics of the *BV*
BV connection status	Binary information	Connected/disconnected value
Preferences/constraints of each *BV* owner	Minimum level of energy desired in the battery and desired time to disconnect the *BV*	Specific data other than stored information
BV battery *s.o.c.*	Percentage	Key criterion for *BV* deployment
Power flow from the *BV* battery to the grid	Signed power quantity	Required for payments

Full-size table

We show in Fig. 13 a schematic which illustrates the interconnection of the components that make up the computer/communication/control network. The elements of the network are the links and the associated subnetworks for communicating with the various players and locations. Specifically, the principal links are the *ISO*/*RTO*-Aggregator, the *ESP*-Aggregator, the Aggregator-parking lot and the Aggregator-residence. In addition, there are the local subnetworks at each location where the *BV*s can be plugged in – be it at a parking lot or at a *BV* owner's residence. The bi-directional *ISO*/*RTO*-Aggregator link is used for the information transfer to enable the provision of MW and MWh services to the bulk power system. In addition, this pathway serves to transmit the billing data to the *ISO*/*RTO*. The fast response times and secure data transmission requirements on this link make computer communications the most appropriate technology to be deployed. Similar requirements and technology solution hold for the *ESP*-Aggregator link whose function is to transmit the signals from the *ESP* to the Aggregator to effectuate the controls to levelize the loads. The Aggregator-parking lot and Aggregator-residence links serve to transfer the signals received by the Aggregator from the *ISO*/*RTO* and the *ESP*s to the various locations where the *BV*s are plugged into the grid. These pathways also allow the transmission of the *BV* monitoring data to the Aggregator and the billing information to the *BV*s. Each local subnetwork in a parking lot or at a residence enables the sending of the command signals from the Aggregator to each individual *BV* for the charging or the discharging of the *BV* battery. Each local subnetwork also serves to collect the monitoring data from the aggregated *BV*s. Such subnetworks are needed since one is required at each location where *BV*s can be plugged in.[10]



Full-size image (41K)

Fig. 13. Computer/communication/control network for the framework proposed.

Given the multiple interfaces between the various links and the associated subnetworks, the accommodation of analog signals for measuring and monitoring the variables of interest, the use of computer commands and the wireless medium in the local subnetworks, the interconnection of the numerous components to construct the computer/communication/control network results in a multimedia system. A particular requirement for this integration to be effective is to ensure the reliability of the entire infrastructural network which cannot be stronger than that of its weakest link. We illustrate the discussion on the implementational aspects with concrete examples of the deployment of available technologies. The illustrative examples simply serve to indicate possible approaches to solve specific problems. The actual implementation may, however, differ considerably from the illustrative approach proposed here.

Virtually all components, with the exception of the local subnetworks, can be implemented using mature technology.[11] However, the local subnetworks which directly link the *BV*s to the parking lots or the residences require an interface with the smart-grid capabilities of the grid. Thus, the local subnetworks must embody the smart-grid features to allow the seamless transmission of data. These subnetworks also provide the means to uniquely identify each *BV* that is plugged into the grid. We make the assumption that each *BV* is fully characterized by its battery for its integration into the grid. A particularly appropriate solution for the *BV* identification is to have the identification system embedded in the battery. For example, it is possible to use *SIM* cards, which can be easily inserted into a small slot in each battery to provide the mechanism for this purpose. The main advantages of the *SIM* technology are its reliability and its flexibility, as indicated by the many years of excellent experience in mobile phones (Mayes and Markantonakis, 2008).

We investigated the development of a practical approach for the signal transmission in this subnetwork and assessed and compared different technology alternatives.[12] We selected a wireless network with *ZigBee*[13] technology. We picked wireless technology to harness the rapid advances in that technology and to minimize the investments costs. The excellent capabilities of wireless technology can easily meet or exceed the requirements for the whole computer/communication/control network. Indeed, the low cost of a *ZigBee* transceiver – less than 1% of the costs of a battery – is an attractive feature of this technology. The cost may be further reduced once it is deployed on a large scale. The *ZigBee* transmission rates of 20–250 kbs are fast enough to transmit the data needed every *second* as is required for frequency regulation services. The range for the *ZigBee* technology can easily extend to 400 m and is adequate to reach every *BV* in a large parking lot with only a small number of transceivers. The use of wireless technology has the flexibility to allow additional devices on a network without modifying its structure. The *ZigBee* technology offers the ability to connect up to 65,000 devices on a single network. Experience to date indicates that *ZigBee* is reliable for home appliances and shows remarkable performance.[14] The cyber security aspects of *ZigBee* have been investigated in power systems distribution networks as *ZigBee* appears to be an important player in demand response applications[15] (Lemay et al., 2008). The deployment to *BV*s is rather similar to such networks (Lemay et al., 2007).

An equally important challenge is the design of an incentive program to ensure the adequate participation of the *BV*s into the aggregation. Not only does the program need to attract new *BV* owners, it also must retain existing participants. The conceptual idea which is proposed here for the incentive program is the creation of a *package deal* by the Aggregator to allow the *BV* owners to do *single-stop shopping*. In return for signing the participation agreement, the Aggregator provides the *BV* owner preferential rates for the acquisition of the battery. The Aggregator also provides the maintenance of the *BV* battery and discounts in the rates for the *BV* battery charging and parking. In return, the *BV* owner is obligated to plug the *BV* into the grid at times specified in the agreement. A simple incentive scheme can provide more and better benefits for a longer term of the contract. In fact, the design of the program calls for rewarding each customer who signs the longer term contracts a guarantee for the *BV* battery and lower tariffs for the operation of the *BV* – be it for the battery maintenance, charging or parking – than to customers who commit for a very short time. On the other hand, the customers who fail to meet the obligation to plug in their *BV*s are penalized and receive no discounts at all.

A key cost component in the operation of *BV*s is that of the battery – its day-to-day maintenance and the costs of its eventual replacement. An Aggregator collecting a large number of *BV*s represents a large buying power. As a large quantity purchaser, the Aggregator receives lower prices per unit of commodity – be it for electricity or for batteries – than that paid by a small individual customer. Furthermore, we can expect the presence of not a single but many

Aggregators. The entry of such large buyers into the market may provide the appropriate stimulus to battery manufacturers to both improve the battery technology and bring about enhanced performance by their products. Market pressures may bring about the co-existence of a limited number of substitutable battery technologies. By developing preferential relationships with battery manufacturers, the Aggregators benefit from preferential prices and conditions for battery purchases, e.g., extended warranty or guarantee. Along the way, the Aggregators will acquire the appropriate *know how* to properly maintain the batteries so as to improve their life expectancy.[16]

The Aggregators can then pass some or all of the savings to the individual *BV* owners through the provision of discounts for battery and electricity purchases. In addition, the Aggregators can provide the battery guarantee and maintenance as part of the *package deal*. The preferential rates for purchasing electricity are very important for individual *BV* owners in light of the growing concern about the higher energy prices and their marked impacts on a household's monthly expenditures. In addition, because of the provision of battery maintenance and guarantee, *BV* owners are more inclined to participate and plug in their *BV*s as they need no longer be concerned about battery degradation due to the operations of the Aggregator. Because *BV* owners get preferential rates for acquiring and charging their *BV* battery, the costs of owning and operating a *BV* can be reduced for every individual owner from what they could otherwise be absent the Aggregator.

BV owners also wish to benefit from using “green” transportation. By driving a *BV* instead of a vehicle with an internal combustion engine, a *BV* owner may participate actively in decreasing CO_2 emissions. *BV*s are viewed as more environment friendly than conventional internal combustion cars due to no or lower tailpipe emissions. Indeed, studies indicate that *BV*s are cleaner even if electricity generation uses fossil fuel sources (MacKenzie, 1994). In addition, the services provided by the *BV* aggregation allow the delay of the start-up of old units, thereby consequently decreasing the emissions from older and dirtier plants. The loads due to the charging of *BV*s during off-peak conditions at night further decrease plant emissions by lowering the need to stop and start-up units for regulation. The inclusion of parking at preferential rates provides incentives for *BV* owners to plug in so as to be able to actively continue their participation in creating a greener environment.

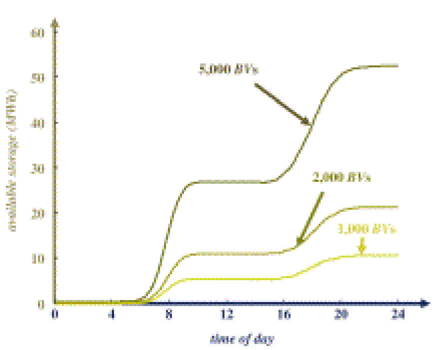
The success of the *package deal* requires compliance by the *BV* owners with the obligations stipulated in the contract. For the *BV* owners who fail to meet the obligations specified in the contract penalties are imposed. Such penalties can include the loss of the battery guarantee and/or maintenance services and may entail the termination of the contract. The carrots-and-sticks package design aims to reward well-performing *BV* owners by increasing their benefits through the various discounts for services and battery operation/maintenance program. However, the *BV* owners who fail to participate are unable to take advantage of these discounts. There is no advantage to the Aggregator to collect such entities and the package will provide no benefits to them.

The Aggregator signs with every individual *BV* owner a *boiler-plate contract* which specifies what is included in the *package deal*. The Aggregator can take advantage of the available battery technologies to get a uniform battery technology aggregation which is easier to manage and maintain. Once the Aggregator has signed on a substantial number of *BV*s, there is adequately large capacity to be of interest to an *ISO*/*RTO*. The services provided by the *BV*s can be an additional source of income to the Aggregator and some of the revenues may be used to improve the preferential rates to the *BV* owners. Similarly, because the *BV*s in the aggregation may be plugged in at locations served by different *ESP*s, the Aggregator may negotiate with more than one *ESP* for the purchase of energy at discounted rates. This also allows a *BV* owner to occasionally plug in the vehicle at a location not served by the *ESP* providing electricity supply to his residence.

The *package deal*, thus, provides a way to the Aggregator to attract a sufficient number of *BV* owners to create an aggregation of a sizeable impact. As a result, the *BV* owner benefits from the preferential rates for the operation and maintenance of the *BV*.

We have applied the framework to perform various simulation studies aimed at quantifying the benefits that can be harnessed from *BV* aggregations. The studies explicitly consider the variability inherent in the behavior of the *BV* owners in terms of individual *BV* owner schedules and the variability across different *BV* batteries (Guille, 2009). The key assumptions used for this study are that the *BV*s are used only for commuting purposes and that the all *BV* owners have similar behavior and driving patterns in that they all go to work every day and park there for some period of time. We present representative results to illustrate the utility of the proposed framework.

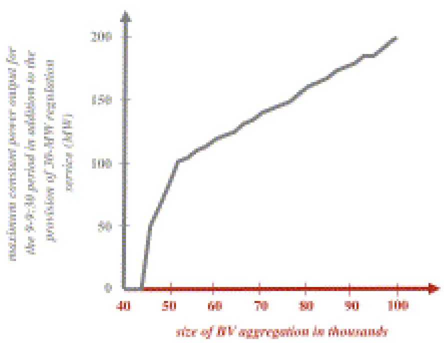
We provide in Fig. 14 an illustration of the useable storage as a function of time. We note that the shape of the evolution of the available storage with time is the same for different sizes of the *BV* aggregation. We also remark that, despite the periods during which the *BV*s are not plugged to the grid, a large storage capability – of the order of MWh – is always available to the grid. The storage capability increases as time goes on because the *BV*s use part or all of the energy stored in their batteries for transportation. Consequently, when they get plugged into the grid after being utilized for transportation, more energy can be stored in the batteries than at the time they left for their journey. Such storage capability can be effectively harnessed by the Aggregator so as to provide important services to the grid.



Full-size image (22K)

Fig. 14. Useable storage from the *BV* batteries for aggregations of 1000, 2000 and 5000 *BV*s as a function of time.

We simulated in some studies the provision of reliable *up* and *down regulation* service and load shaving energy with aggregations of varying numbers of *BV*s. In one set of studies, we consider the case in which the *BV* aggregation is requested to provide a 30-MW regulation service from 8 a.m. to 6 p.m. as a contribution to serve the reserve requirements coupled with the provision of energy for load shaving from 9:00 a.m. to 9:30 a.m. The results indicate that the ability to provide the services improves as the size of the *BV* aggregation increases, as shown in Fig. 15. The provision of the two services requires an aggregation of at least 45,000 *BV*s. An aggregation of 100,000 *BV*s can provide up to 200 MW of constant power output over the half *hour* period.



Full-size image (21K)

Fig. 15. Maximum constant 30-min power output a *BV* aggregation can provide in addition to the provision of 30-MW regulation service as a function of the aggregation size.

6. Conclusions

In this paper, we present the development of a proposed framework for the implementation of the *V2G* concept. The framework shows the range of services the *BV*s, once aggregated and connected to the grid, can provide. *BV* aggregations can act as controllable loads that contribute to levelizing the off-peak load at night or as generation/storage devices that can provide *up* and *down regulation* service and peak shaving energy when the vehicles are parked during the day. The framework recognizes the central role of the Aggregator in *V2G* and can appropriately accommodate its critical role in collecting the *BV*s to form aggregations and dealing with *ESP*s and the *ISO*/*RTO* for the purchase/provision of energy and capacity services. In addition, the framework provides the means for incorporating the computer/communication/control infrastructure to represent the flows between the *ESP*s or the *ISO*/*RTO* and the individual *BV*s. By explicitly taking into account the physical characteristics of the *BV*s, the framework provides sufficient flexibility to be used for operations and planning purposes. To bring the *V2G* concept closer to reality, we also present proposed approaches to deal with two major issues in the implementation of the framework. We outline the design and structure of the computer/communication/control system to enable the required data transfers between the Aggregator and the *BV*s as well as between the Aggregator and the *ESP*s and the *ISO*/*RTO*. In addition, we present the design of an incentive scheme for the Aggregator to attract and retain *BV* customers using a *package deal* concept. In the proposed design, the Aggregator provides preferential rates for *BV* charging, battery supply and maintenance and parking services in return of the obligation for the *BV* owner to plug the *BV* at specified times.

While the framework coupled with the approaches proposed for two key implementational challenges constitutes a major step to bring the *V2G* vision closer to reality, considerable work still needs to be done. For example, there is a need to focus future research efforts on the improvement of the *BV* selection so as to enhance the life expectancy of the *BV* batteries. There is also a need for governments to promote the adoption of *BV*s through the promulgation of new regulations. Such regulations encompass a broad scope and will need to include incentives for *BV* owners. As the *BV* penetration grows, the *BV*s will represent a larger fraction of the total *ESP* demand and the meeting of this demand will receive regulatory oversight. The regulators will need to understand the nature and impacts of *BV* integration into the grid so as to formulate appropriate policies. Their role will be crucial in further stimulating the encouragement of *BV* penetration in a responsible manner.

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[1] See http://acta.us/growls/2008/02/where_do_us_oil_imports_come_f.html (read on April 10, 2009).
[2] See for the stimulus plan: http://blogs.consumerreports.org/cars/2009/03/24-billion-for-vehicle-battery-and-plugin-electric-car-development.html (read on April 9, 2009). For FERC news: http://news.morningstar.com/newsnet/ViewNews.aspx?article=/DJ/200901261337DOWJONESDJONLINE000483_univ.xml (read on April 10, 2009).
[3] L.M. Brass, "ORNL study shows hybrid effect on power distribution", news release, Oak Ridge National Lab, March 12, 2008.
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[5] Delivery trucks such as *UPS* or *FedEx* trucks may have bigger batteries but have not been equipped with such technologies so far. *Arotech* manufactures an electric bus which has battery storage of 312 kWh.
[6] Most of the *BV* batteries which are taken into account in this study are lithium-ion batteries as this technology seems to be adopted most widely by various battery manufacturers.
[7] The locational marginal price at a node measures the cost to serve the next increment of load at that location in a system that is optimally dispatched.
[8] These fluctuations are monitored using the so-called area control error (*ACE*) which is, typically, computed every 2–4 s. A positive (negative) *ACE* requires the reduction (increase) of the frequency by lowering (raising) the generation outputs of the units participating in the provision of regulation service.
[9] Department of Market Monitoring, "Annual Report on Market Issues and Performance," California ISO, April 2007.

[10] Such locations include the parking lots, the residences or the charging stations if they are implemented. The installation of the subnetworks will then require a massive investment.
[11] See http://www.greencarcongress.com/2008/02/v2green-technol.html (read on April 10, 2009).
[12] Other technologies which may be considered include *bluetooth* and *BPL*.
[13] *ZigBee* is the name for a combination of high-level communication protocols using small, low-power digital radios based on the IEEE 802.15.4-2006 standard.
[14] See http://www.sensorsmag.com/sensors/Wireless+Works/How-ZigBee-Compares/ArticleStandard/Article/detail/393407 (read on April 10, 2009).
[15] For example, solutions have been developed to have a laptop recharge its battery, or a fridge begin its cooling cycle, only when the electricity price is low.
[16] The incentive scheme proposed here is distinctly different from the battery exchange scheme at various recharging stations proposed by the *Better Place* model of Shai Agassi. The *Better Place* model can be found at http://www.betterplace.com/our-bold-plan/business-model/ (read on April 10, 2009).

Vitae

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