A CONCEPTUAL FRAMEWORK FOR THE VEHICLE-TO-GRID (V2G) IMPLEMENTATION

BY

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THESIS

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ABSTRACT

The quest for energy independence and rising environmental concerns are key drivers in the growing popularity of battery vehicles or BVs – electric and plug-in hybrid cars. Studies indicate that for 90% of the Americans who use their cars to get to work every day, the daily commute distance is less than 50 km – or 30 mi – and, on the average, the commuter car remains parked about 22 h per day. The BVs have in common the batteries, which provide storage capability that can be effectively harnessed when the vehicles are integrated into the grid. The entire concept of using the BVs as a distributed energy resource – load and resource – is known as the *vehicle-to-grid* or *V2G* concept. The thesis outlines a framework for implementing V2G.

A thorough analysis of battery characteristics provides the basis to determine which services BVs can provide. As each individual BV represents only "noise" to the power system, the BVs need to be grouped into large aggregations whose combined impacts can be felt by the grid. We investigate the deployment of a BV aggregation for the provision of frequency regulation and energy supply for load shaving. Similarly, we study the impacts of such an aggregation on levelizing the loads during the off-peak periods including the utilization for down regulation service.

We develop a modeling approach in order to take into account the variability inherent to the behavior of the BV owners and the variability among the BV battery characteristics. We show that for aggregations of sufficient size, the effect of the uncertainty related to the behavior of the individual BVs can be smoothed out and that, consequently, the aggregated BVs are a reliable resource. Such a result emphasizes the

importance of the Aggregator in making sure that the modules corresponding aggregated BVs are of large size.

The framework makes effective use of the BV aggregation but leaves the identity of each BV unchanged. Conceptually, we may view the framework to consist of a physical layer, where the flows are megawatts, megawatt-hours, 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. The framework provides a basis for planning and operations purposes as it takes into account the physical characteristics of each individual BV.

To ease implementation of the framework, we propose approaches to tackle two key implementational challenges. We present an approach for the computer/communication/control network that can be fully integrated into the smart grid to enable the integrated battery vehicles to effectively participate in the operation of the grid and electricity markets. We propose an incentive scheme based on the notion of package deal to enable the attraction and retention of BV customers into the V2G program. The proposed approaches tackle two of the most critical challenges to making V2G a reality.

We make use of the framework to perform a number of simulation studies to quantify the benefits that can be harnessed from BV aggregations. We carry out sensitivity studies to assess the ability of BV aggregations of different size to provide regulation and load shaving services during the day and to reduce the regulation down requirements at night. We show that the deeper penetration of BVs into the grid has real positive impacts on both the load and resource sides. We also point out the synergistic relationship between the integration of BVs into the grid and that of wind power. BV aggregations can facilitate the integration of wind farms into the power system by flattening their power output.

The development of the framework together with the approach proposed for two key implementational issues provides a contribution to furthering the state of the art in V2G implementation.

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1. INTRODUCTION

In this chapter, we establish the setting for the problems we deal with in the thesis. We start by discussing the motivation for the work presented in the thesis. We also give the current state-of-the-art in both academic research and industry developments in the field of the thesis. We then present the main contributions of the present thesis and provide a brief outline of the remainder of the report.

1.1 Motivation

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, is the key driver 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 BVs in the form of either plug-in hybrid vehicles (PHEVs) or all-electric vehicles (EVs) is directly addressing these issues. The common characteristic of EVs and PHEVs 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 BVs. 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. Because of all the various activities underway, we can expect a massive deployment of BVs over the next few years. Such an exploding growth creates both a new load class for charging the batteries and new opportunities for the effective integration of BVs into today's grid. FERC recently communicated via its chairman on the essential need to integrate electric vehicles into the national power grid [2].

Given the nature and physical characteristics of BVs, 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 BVs, 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 bidirectional power transfers are possible once the interconnection is implemented. Indeed, the integration allows the deployment of BVs 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 BVs as a generation/storage device in this case. The entire concept of using the BVs as a distributed resource – load and generation/storage device – by their integration into the grid is known as the vehicle-to-grid or V2G. Under this concept, the BVs become active players in grid operations and play an important role in improving the reliability, economics and environmental attributes of system operations. However, V2G is still in the thinking stages and is waiting for its implementation – a daunting challenge particularly for deep penetration of BVs.

In this thesis, 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 BVs 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 BVs can play. As a load in the charging phase during the off-peak conditions at night, the BV aggregation may be deployed to levelize load, thereby contributing to lowering the need for down regulation service during those periods [3]. As a resource during the day, when the BVs are parked, the BV aggregation can provide up and down regulation service, as well as peak shaving energy. In this way, the BVs act as both a generation source and a storage device. The Aggregator who collects the BVs 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 or ESPs 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 thesis.

The recent developments are not the first time in the history of car manufacturing that EVs have been prominent. The very first EVs appeared in the 1830s before the internal combustion engine was developed and continued. Until the breakthrough created by the Ford Model T in 1908, the early EVs led the market in terms of both performance and market share [4]. Starting in the 1990s, a new interest in EVs and also hybrid[1] vehicles arose, but the sales have not yet reached significant levels. More recently, there has been a very strong and increasing interest in PHEVs[2]. Some of the leading players include the Tesla Roadster and the Miles Electric Vehicles. BVs driven in electric mode offer very high performance in terms of acceleration and noise comfort but are limited in their range – under 190 mi or 300 km – and the time needed to recharge their batteries is rather long, of the order of 5 h. Due to their limited range, these vehicles are typically used for commuting purposes. Research to overcome the range limitation of BVs is a key objective in the Department of Energy research plan [5].

BVs are attractive because they can drastically reduce CO_2 emissions. In 2007, the California Air Board[3] adopted a state alternative fuels plan to promote cleaner fuels [6]. This plan recognizes that plug-in hybrid vehicles and biofuels are cleaner than hydrogen

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[1] To reduce oil consumption, hybrid vehicles have been developed. The internal combustion engine is coupled with an electric engine which provides part or all of the energy necessary for the propulsion of the vehicle. The battery necessary to run the electric engine is recharged using the internal combustion engine or taking its energy from regenerative breaking.

[2] PHEVs are closely related to the current hybrid vehicles. PHEVs basically replace the standard batteries of the hybrid vehicles with batteries of higher storage capability and come with a plug to allow battery charging. Some companies, such as Edrive Systems, market conversion kits for making the hybrid vehicles plug-in ready. Unlike the standard hybrids, PHEVs can run on a purely electric mode. The classification of PHEVs is based on their range in this electric mode with PHEV 20 for the 20 mi (32 km) range, PHEV 40 for the 40 mi (64 km) range and PHEV 60 for the 60 mi (96 km) range. PHEVs are usually viewed as a more practical approach to overcoming the distance limitation than EVs as they can use their internal combustion engines as a viable backup.

[3] The state of California has been the leading state for clean transportation.

fuel cell cars. Other studies also show that electric cars reduce greenhouse gas emissions by more than fuel cell hybrid vehicles [7]. All the BVs reduce pollution because there are no tail pipe emissions produced by a car driven in the electric mode. The energy needed for the BV to be driven is produced by power plants and, thus, the environmental benefits are highly variable from region to region and depend on the resource mix installed in the region.[4]

For the power industry, the ability of the current system to accommodate the additional load of the BVs 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 [11]. However, with smart grid technology [12], 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 the California grid of 4 million PHEVs – 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 [13]. In fact, the small change in the total demand with all the PHEVs 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 PHEVs in Fig. 1.1. In California, in fact, the BVs 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

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[4] For example, for developed countries, the CO_2 emissions per km can range from 40 g/km for France to 150 g/km for Germany for a given vehicle [8], [9], [10].

can maintain a continuous steady output even during the off-peak periods by charging the BVs.

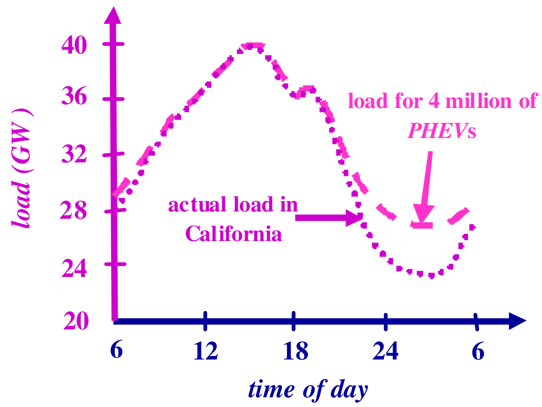

Figure 1.1: The California daily load with and without PHEVs for a typical summer day

1.2 Survey of the State of the Art

The V2G concept is still in its infancy. However, many industry and academic entities are currently involved in the development of BVs, the advancement of battery technology for BV applications and various projects related to furthering the V2G concept. We present in this section a brief summary of the state of the art and of the current developments in bringing V2G to reality.

BVs are at the center of the V2G concept. Hybrids and a few electric vehicles have been on the market for a few years now. The tremendous success of the Toyota Prius has provided the stimulus for the other car manufacturers to develop new models.[5] The marketing efforts for these new vehicles have been very successful and the waiting lists to get a BV keep getting longer. The concerns about energy efficiency as well as the

[5] Chrysler for example announced in 2008 that it would introduce three new BVs by 2010. Similarly, GM plans to start producing the Volt during the same year and Renault has plans to make the electric car an attractive option for its customers by 2011.

technological improvements have been major reasons for the strong acceptance of the new BVs.

The main areas of progress in BV technology include power electronics and battery technology. As far as power electronics are concerned, the improved efficiency of the energy conversion as well as the reduced size of the equipment have been important steps forward. Such improvements have been instrumental in improving the range of the BVs and their acceptance for commuting purposes. However, the road ahead still presents many challenges in terms of the volume of production, weight and costs of the devices for the BVs [14].

The interest from car manufacturers has drawn attention to the area of batteries. Since the initial battery technology enabled the development of the early BVs, many battery firms have entered the market.[6] Nickel metal hydride (NiMH) and lead acid battery technologies have been widely applied to BVs [15]. In order to improve the power density of the battery and consequently increase the range of the BVs, lithium ion (LiI) batteries have been designed. This new technology has better performance, but serious safety issues still need to be addressed. Research efforts are now focused on improving the safety, overcoming the range limitation and monitoring the battery degradation so as to improve the life expectancy of the batteries and make BVs an even more attractive option for transportation [16].

All the BVs need to be connected to the grid to get part or all of their energy for transportation. The charging infrastructure has to be ready for BVs to be plugged into the

[6] Some of the active players are A123Systems, LG Chemical, Panasonic EV Energy Co (PEVE), JCS and Bollore.

grid. Car manufacturers, such as Tesla Motors, have designed charging stations to enable the BV owners to charge their BVs at their residences. Only a few charging stations have been installed in parking lots so far and the installation is usually performed on very specific areas. For example, three charging stations have been installed by Coulomb technologies as part of a demonstration project in San Jose [17]. Similar charging station networks of bigger size are currently under installation in different parts of the world.[7] The charging stations that are being installed offer bidirectional transfer capabilities though they have not been used so far for sending power back from the BV batteries to the distribution grid. Other companies adopt a somewhat different approach and propose the implementation of battery exchange stations. The concept consists in offering stations at which the discharged BV battery is removed automatically from the BV and a charged battery is installed in the BV. The functioning of the stations still has to be demonstrated.

The current power system is able to withstand the load created by the BVs. The research done – usually of regional nature – shows that overnight charging has a rather small impact on the transmission system [18]. The distribution system can also accommodate the new load without any modification [19].

The V2G concept has been introduced recently and some early description of its benefit has been performed [20]. Under V2G, the BVs can participate actively in grid operations. BVs can be more than just a load and can be used for applications which do not require the provision of big amounts of power over a long period [21], [22], [23]. In

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[7] Renault and the French electric utility EDF, for example, signed in 2008 a memorandum of understanding to create a large-scale zero-emissions individual transport and travel system.

addition, it was shown that the BV batteries can be used in a synergistic manner with photovoltaic cells and wind turbines to act as storage devices [24].

To show the feasibility of the integration of BVs into the grid, a few demonstration projects have taken place. The studies were performed using a modified BV which could respond to the command of the ISO/RTO by charging or discharging its battery. The results indicate that an individual BV can actually provide regulation service to the grid.[8]

The BV technology is ready for BVs to be accepted more widely for commuting purposes. Major improvements in power electronics and battery technologies have enabled the car manufacturers to improve the range and the performance of BVs. The technology for bidirectional charging stations is also available and more and more charging stations are being installed. Several studies have shown that the current system has the ability to accommodate the load created by a number of BVs representing up to 50% of the total US fleet. In addition, the potential of BVs to provide capacity and energy services to the grid has been shown through theoretical studies and demonstration projects.

While the work done was very useful, several needs still have to be fulfilled. The performance of the battery still needs to be improved through the use of new technologies or by better managing their usage. As far as the integration of BVs into the grid is concerned, a blueprint is necessary to make the implementation of V2G possible. The roles of the different entities need to be clearly defined. In addition, none of the studies

[8] Xcel Energy and PG&E have V2G programs which include demonstration on small fleets of BVs.

has explicitly considered the variability in the behavior of the BV owners and the resulting uncertainty. The studies were done under the unrealistic assumptions that all the BVs are always plugged into the grid and that an infinite amount of energy can be taken from their batteries. Furthermore, no computer/communication/control network has been implemented so far for the control of the charging and discharging of the BV batteries plugged into the grid. The existing power system is undergoing many changes so as to integrate smart grid technologies. An interface with the smart grid needs to be provided for better integration of the BVs into the grid.

1.3 Scope and Contribution of this Thesis

In order to address the needs identified in Section 1.2, we propose a framework for the implementation of V2G. Motivated by using our power systems insights, we present a construct to allow the effective integration of BVs both as a load and a generation/storage device into today's existing distribution grid. The work shows the range of benefits BVs can bring to power systems by increasing the load at night but also providing capacity and energy services during the day when the BVs are parked. Each individual BV battery can only have a negligible impact on the power system because of its small power output. To solve this problem, the concept of BV aggregation is at the heart of the proposed approach. The aggregation can also bring about advantages in terms of the scale of impacts and economies of scale. The framework takes fully into account the physical characteristics of the BVs and explicitly recognizes the uncertainty inherent to V2G. 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. The modeling work helps us to represent the variability of the behavior of the BV owners' and of the diversity among the batteries. The work also includes practical approaches for solving two key implementational steps – the design of a computer/communication/control network and of an incentive program.

The comprehensiveness of the framework is illustrated through many numerical studies. The statistical laws which apply to the BV aggregations can smooth out the heterogeneities resulting from the behavior of the BV owners. One study shows that considerable storage from the BV batteries can be used by the grid to improve power system operations at any point in time. A case study illustrates the potential of using BVs to provide daytime regulation service and load shaving. The charging of the aggregated BVs at night also helps in reducing the off-peak regulation down requirements. The services provided can be of very significant impact if the size of the aggregation is large enough. The framework provides the tools to quantify the minimum number of BVs that need to be aggregated in order to provide services. We also illustrate the operations of the framework in showing the synergies between the integration of wind power into the grid and that of the BVs. The BV aggregations can smooth out the power output of wind farms by sending power back to the grid when the wind speed does not allow generation to occur and by absorbing power when the power output of the wind farm is too high.

1.4 Outline of the Thesis

This thesis consists of five additional chapters and three appendices.

In Chapter 2, we present the salient characteristics of a BV battery and of the usage of the BVs. We introduce the SOC variable used as a determinant for the battery usage. We present the demand- and supply-side roles of an individual battery as a function of its SOC. We also point out that as each BV battery represents simply "noise" to the power system in light of its storage capability and its power output, there is a need to group BVs in aggregations for them to have an impact on the grid.

In Chapter 3, we develop the roles of the Aggregator. Benefiting from the buying power of a large group, the aggregator can then obtain lower rates for battery provision and other services and pass them to the individual BV owner. Then, we investigate the roles of aggregated BVs as distributed energy resources. We show that BVs can play the role of a controllable load but can also provide capacity and energy services. In order to represent the uncertainty inherent to V2G, we develop a modeling approach which makes full use of the nature of the aggregation.

In Chapter 4, after setting up the necessary assumptions, we construct a two-layer framework for V2G. We introduce the physical and information layers and detail their characteristics. We also show the flows on the two layers. We bring to the fore the implementation of the information layer by proposing an approach for the computer/communication/control network. We detail its main requirements and components of the network and propose an approach based on wireless technology for one of the subnetworks. We also propose incentives based on the one-stop shopping concept and making use of a package deal for BV owners.

In Chapter 5, we go further than the conceptual approach and provide simulation results for different applications of the integration of BVs into the grid. One of the case studies consists in the provision of daytime regulation service and load shaving by BV aggregations of different size. We also show how regulation requirements at night can be greatly reduced by plugging in the BVs. Another study shows the synergies between the integration of wind power into the grid and V2G. We point out the smoothing out of the power output of a 56 MW wind farm by an aggregation of BVs.

Chapter 6 summarizes the key results of our studies and points out directions for future work for the implementation of V2G to be successful.

In Appendix A, we provide the definition and the main characteristics of the truncated normal distribution which is used in the modeling approach presented in Chapter 3.

In Appendix B, we present the simulation procedures which have been used for the simulations involving the provision of regulation service and load shaving.

In Appendix C, we describe the characteristics of the wind farm which was used for the wind simulation in Chapter 5. We give the typical wind power curve and detail the wind turbines which were chosen. We also provide explanations of the case study and a flowchart of the simulation procedure.

2. CHARACTERISTICS OF THE BV UTILIZATION AND THE BV BATTERY

This chapter describes the characteristics of the BV batteries and the utilization of BVs. The two fundamental characteristics of BVs of interest to this work are that they are vehicles and that their batteries can both generate and store electricity. As vehicles, they are used for transportation purposes at certain times and may be parked at other times. We take advantage of the fact that, as various studies indicate, commuter vehicles remain parked on average 22 h a day and that the driven distances do not exceed 50 mi on average to harness the BV batteries for effective deployment when interconnected to the grid. We use the state-of-charge of each BV battery to determine its capability to provide services on the supply- or demand-sides to the grid. We also provide the motivation for the need to aggregate BVs together to create a controllable load or a generation/storage device of significant size on the power system scale.

2.1 BV Utilization Characteristics

As vehicles, BVs are not always stationary and therefore may be dispersed over a region at any point in time. In a moving state, BVs 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 BVs for daily commuting purposes. A study for ABC News in 2005 showed that the roundtrip average commuting distance in the US is 32 mi – about 50 km –and the average commuting time is around 52 min with a very large variability: commuting times can be twice the average under certain conditions [25].

Survey data on the commuting patterns of US drivers nationwide indicate that 60% of commuters drive a distance under 50 mi – 80 km. The plot in Fig. 2.1 represents the cumulative percentage of vehicles as a function of the one-way commuting distance [13].

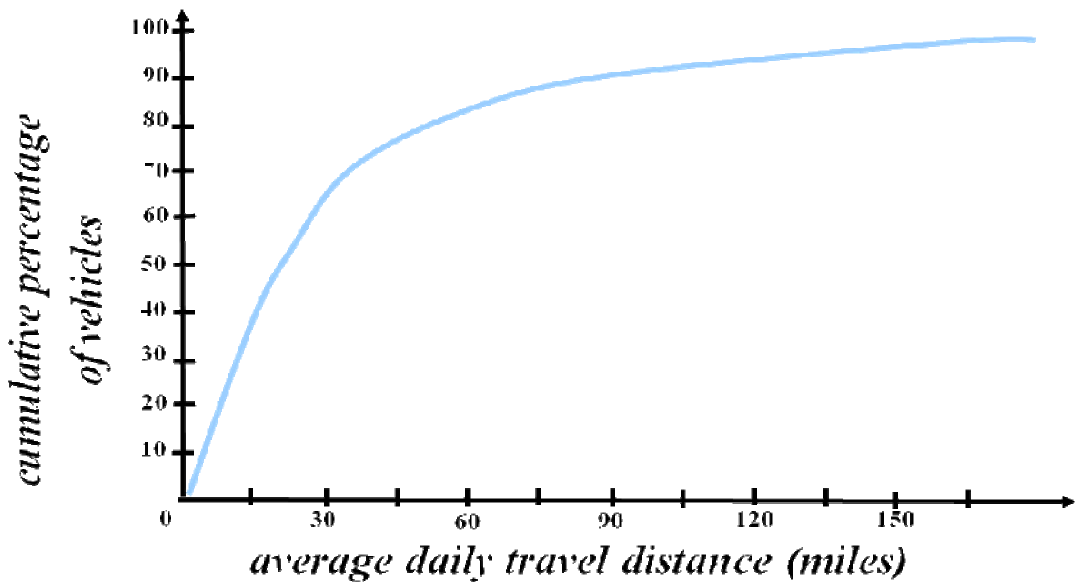

Figure 2.1: Cumulative percentage of vehicles as a function of the nationwide one-way commuting distance

For the BVs used for commuting, we can see, 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 BVs, 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.

2.2 Battery Characteristics

Next we discuss the battery. The typical range for commercial[9] BV battery[10] storage C – also called storage capability – is from 1 to 30 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 [26]. Thus, the battery output is usually in the 0.2 to 6 kW range. The BVs need energy from the BV batteries for their propulsion. We define the efficiency of a BV as the amount η[11] of energy needed to drive one kilometer.

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 – SOC – of the batteries. SOC 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 SOC 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 in the BV for charging during the night, the SOC will evolve along a pattern illustrated in Fig. 2.2.

[9] 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.

[10] 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.

[11] η is usually in the 0.15 – 0.35 kWh/km range.

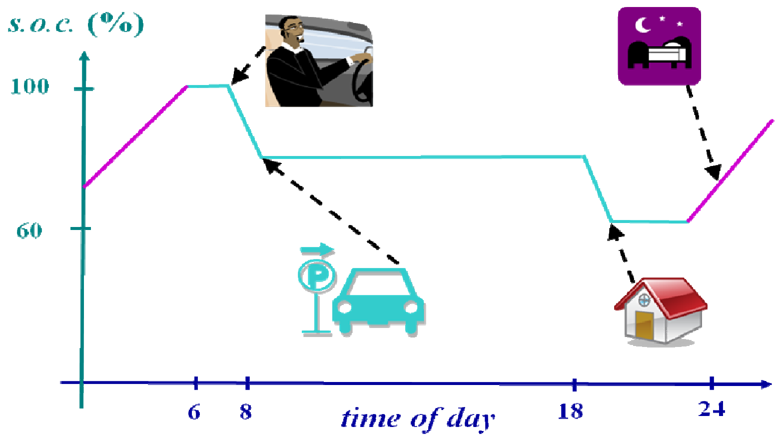

Figure 2.2: Evolution of the SOC of a BV for a typical day

Batteries release energy more easily when their SOC is high or, more precisely, above a tolerance level. We stipulate 60% to be the tolerance level in this work. When the SOC 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 [27]. 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 SOC. The diagram in Fig. 2.3 summarizes this information.

Frequent switching of the SOC may cause a decrease in battery storage capability, which is defined as battery degradation. We use the value of the SOC 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 SOC reaches the 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.

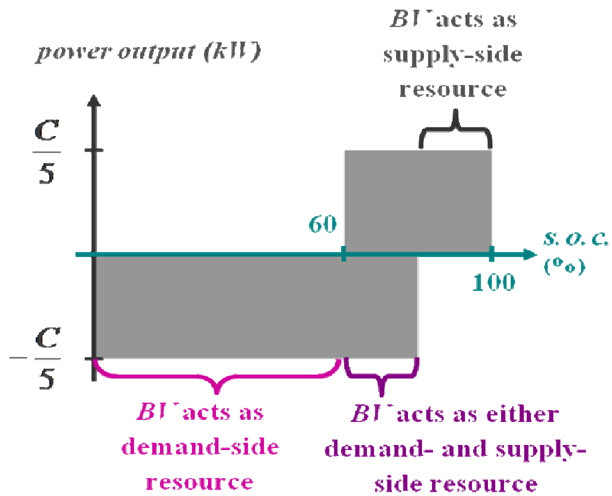

Figure 2.3: The SOC determines the functioning of the battery

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 [28]. 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 theory, once plugged in to the grid, BV batteries may be used as DERs. 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 BVs to be a useful resource, a degree of aggregation is required to bring about a size that can impact the grid.

In this chapter, we have detailed the salient characteristics of the BV as both a vehicle and a battery. We showed that despite the fact that BVs are used for transportation, a lot of energy remains unused in the batteries and the cars are plugged in for at least 22 h. Consequently, the BV batteries can be used as a demand- or supply-side resource. We introduced the state-of-charge as the determinant of the usage of a battery. We noted that BV batteries have small storage capacities and small power output and that, consequently, they cannot have any impact on the grid on their own. They need to be aggregated to be able to provide services to the grid. We devote the next chapter to discussing the nature and the role of aggregations of BVs.

3. BV AGGREGATIONS

Because of their batteries, BVs present an interesting potential as a storage facility. However, the storage capability of the BV batteries is small on the grid scale, and consequently their individual power output cannot have any impact on the power system. For the BVs to be able to play a role when interconnected to the grid, they need to be grouped into aggregations. Once aggregated, they are able to provide different kinds of services, either as a controllable load or as a generation/storage device. However, the BVs may not be always plugged into the grid and their schedules are very uncertain. We develop here a probabilistic model to take into account the uncertainties inherent to a BV aggregation. We show that, despite the uncertainty, the storage available to the grid at any point in time is of a magnitude to be of interest.

In this chapter, we introduce the Aggregator as a key player in the implementation of the V2G concept. We discuss the roles of the Aggregator and the range of services such an entity can provide to the BV owners. We devote a section to the evaluation of the physical and economic impacts of the integration of a BV aggregation into the grid in the dual role of load and generation/storage device. We also discuss the sources of uncertainty in a BV aggregation and propose a modeling approach that can be used for such aggregation so as to explicitly represent the impacts of the various sources of uncertainty. We apply the modeling concepts to BV aggregations of different sizes and provide illustrative examples of the storage provided by such aggregations. The analysis serves to lay the foundation for the motivation of the simulation studies that we report in Chapter 5.

3.1 Roles of the Aggregator

The battery storage of an individual BV is too small to impact the grid in any meaningful manner. As such, a BV connected to the grid constitutes simply noise for the electric system. An effective approach to deal with the negligibly small impact of a single BV is to group together a large number of BVs – from thousands to hundreds of thousands. The aggregation, then, can impact the grid both as both a load and a generation/storage device.

The basic idea behind such aggregation is the consolidation of the BVs 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 BVs by attracting and retaining them so as to result in a megawatt capacity that can beneficially impact the grid. The size of the aggregation is indeed key to ensuring its effective role. In terms of load, an aggregation of BVs represents the total capacity of the batteries, an amount in megawatts 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 BVs 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 BVs can provide. The Aggregator's role is to effectively collect the DERs 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 BVs 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. 3.1. We first discuss the BV aggregation utilization as a controllable load and then as a generation/storage device.

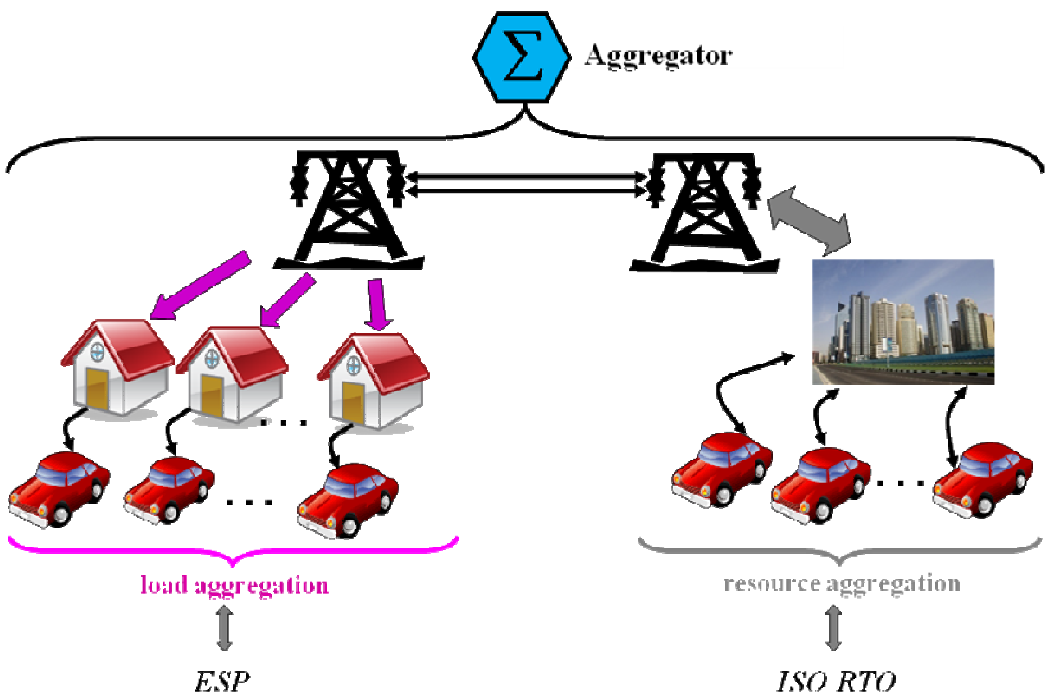

Figure 3.1: The BV aggregation may act as a controllable load or as a generation/storage device

3.2 BV Aggregation as a Load

The charging of the BVs introduces a new load into the system. For every ISO, 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. Figure 3.2 provides the hourly load for Thursday, February 21, 2008.

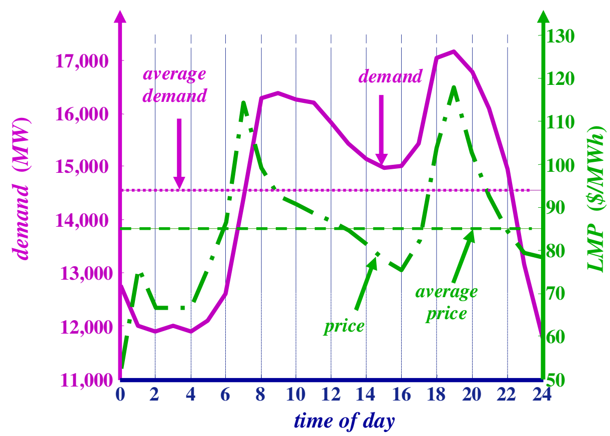

Figure 3.2: Load and price for a typical winter day for NEISO

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. 3.2 of the locational marginal prices[12] or LMPs realized at a node called HC.AYER 115 in the New England ISO system on February 21,

[12] 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.

2008. We note that, at this location, it makes ample sense for the BVs to be charged between 12 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 BVs. 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. Such load levelization is a major contribution to the ISO's operations since the dispatch for a flat load is far less complex than for a fluctuating load. We conceptually illustrate in Fig. 3.3 the impacts of the aggregated BVs into a controllable load on a system whose demand is fluctuating. As a load, therefore, the aggregated BVs can help system operations not only by being a useful sink but also by levelizing the load during off-peak period.

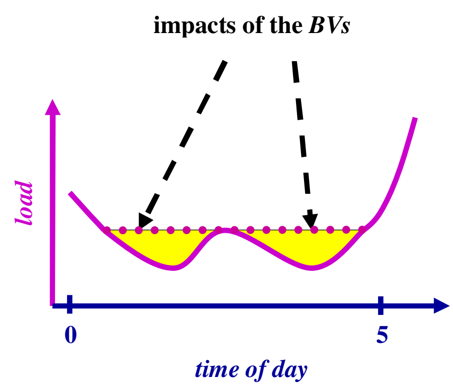

Figure 3.3: The charging of the BVs can be done so as to levelize the load during the off-peak period

3.3 BV Aggregation as a Generation/Storage Device

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[13] 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 SOC. 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. 3.4 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.

[13] These fluctuations are monitored using the so-called area control error (ACE) which is, typically, computed every 2 to 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.

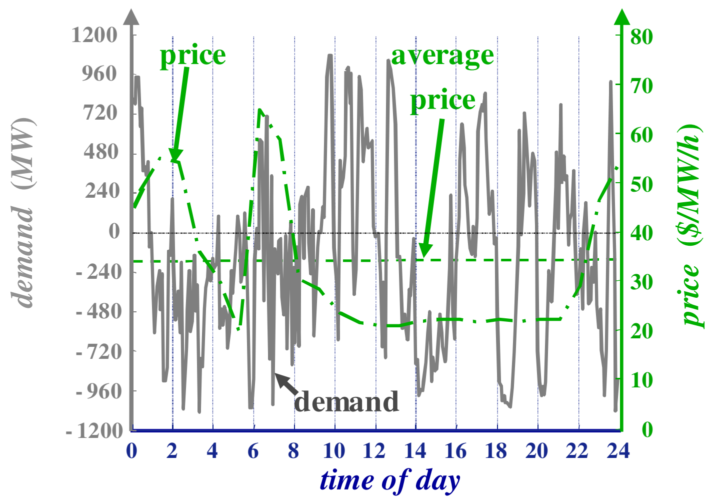

Figure 3.4: Required regulation service and prices for PJM for June 6, 2006

The high prices for nighttime regulation are representative of the situation in other ISO/RTOs. For example, Fig. 3.5 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 in every three nights [29].

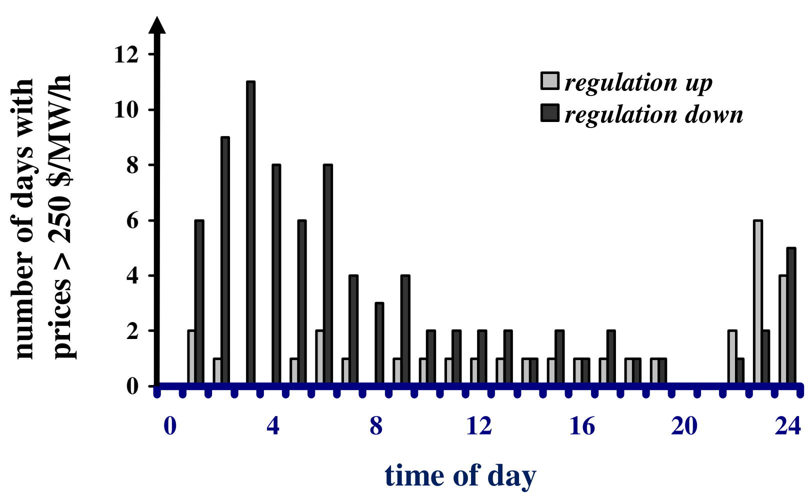

Figure 3.5: Number of days with prices higher than 250 $/MW/h for the regulation service for CAISO in April 2006

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 BVs 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 pickup in the morning.

In addition to lowering off-peak regulation needs, the aggregated BVs may be also deployed to provide daytime 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 SOC of each individual battery, but can do so with a much faster response time than conventional units. The deployment of aggregated BVs 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 BVs to meet the base load has previously been questioned [22], the aggregated BVs may be used to provide reserves to the grid. A sizeable aggregation of BVs can provide considerable support to a system operator by allowing the delay of the startup of the cycling and peaking units. The operator, in order to ensure the ability of the generation system to meet the load during peak conditions, performs startup 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 startup of the cycling and peaking units because of the reliance on the aggregated BVs. We illustrate this notion in Fig. 3.6 for a system for which the BV aggregation may introduce a delay of hours for the startup of the cycling units. We note that BVs provide capacity service here. In case the energy is actually needed, aggregated BVs sell, through the Aggregator, some part of the energy stored in their batteries. In this case, the aggregated BVs also play the additional role of an energy resource.

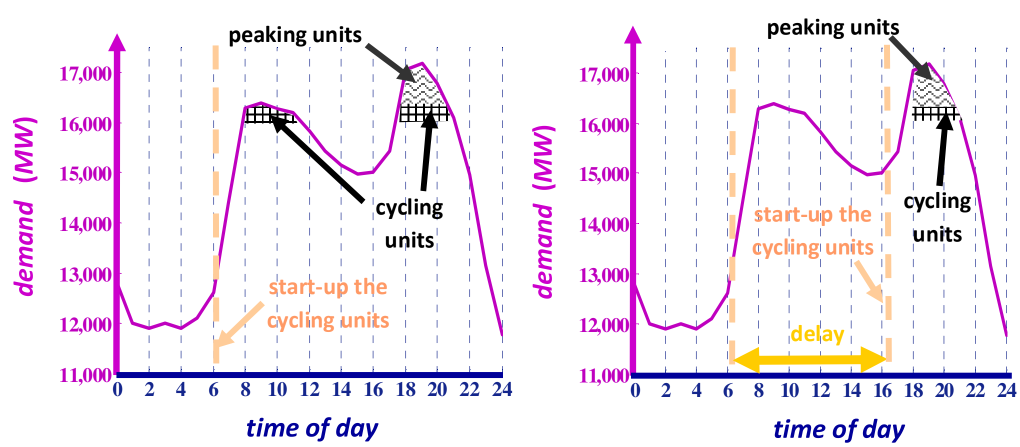

Figure 3.6: BVs provide support service to allow the ISO/RTO to delay the startup of the cycling units by several hours

Aggregated BVs have the potential to play a very important role in improving system operations both on the demand- and the supply-side. However, there is a huge variability in the behavior of the individual BV owner. This variability is a challenge for the Aggregator in order to assess the size of the resource available from the aggregated BVs. In order to study the impacts of such variability, we develop a modeling approach for the BV aggregations.

3.4 Modeling of BV Aggregations

An aggregation of BVs can act as an effective distributed energy resource once it is interconnected with the distribution grid.[14] However, we must keep in mind that the principal utility of BVs is to provide clean and economic transportation to their owners rather than to generate electricity for grid operations. As a result, the aggregated BVs may not always be plugged into the grid. Since BVs may travel different distances every day, they may have different levels of energy stored in their batteries any time they become interconnected to the grid. The aggregation of many BVs serves to smooth out such heterogeneity and to make the aggregated entity behave in a more homogeneous manner. The time dependence of BV travel may impact the level of participation of an individual BV to the load and the generation/storage device roles of the aggregation. The variability in the contribution of each BV to the aggregation creates considerable uncertainty in the capability of the aggregation to act as a resource at any point in time. Due to the personal preferences of each BV owner, the Aggregator cannot know with certainty the individual BV owner schedules and the amount of energy stored in each vehicle's battery when the BV gets plugged in. We analyze the nature of this uncertainty

[14] It makes sense to connect the BVs at the distribution level and not at the transmission level as they are, typically, plugged in at BV owners' residences or in parking lots which are connected to the distribution system.

and construct an appropriate model under a set of reasonable assumptions. We deploy this model to simulate the impacts of a BV aggregation as a load and as a generation/storage device.

The principal sources of uncertainty for an Aggregator are:

- the duration of the periods during which each BV in the aggregation is connected to the grid
- the distances traveled by each BV
- the SOC of each BV at any point in time

To analyze the nature of the resulting uncertainty, we need to introduce assumptions to allow quantification of the resulting randomness. Specifically, we limit our analysis to the following set of assumptions:

- Losses in the BV batteries are neglected.
- The storage capability of each BV battery remains unchanged during the study period.
- All BVs have the same efficiency η.
- Each BV battery has fast response times – of the order of milliseconds.
- BVs are used for commuting purposes only.
- 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.
- Each BV owner is independent of any other BV owner.
- BV owners do not change their BVs during the time of the study.
- Parking lots have big capacities.

- BVs are plugged in when they are parked.
- Charging stations and outlets at a particular location do not have any power limitation and are adequate for the BV which gets plugged in at this location.

Such assumptions are reasonable for the following reasons:

- The losses due to conversion efficiency in the charging stations or in the BV batteries or due to transmissions losses are small – less than 10%.
- All BV batteries, even if they may present small structural differences, have very fast response capabilities to be able to perform their task of providing energy to the BV engine.
- Many BVs cannot be used for long trips because of their limited range. It is then reasonable to think that people drive them mainly for commuting purposes.
- The duration of the study period is of the order of a few days. It seems very unlikely that BV owners get a new BV during this period.
- The aggregation of several parking lots can correspond to a single parking lot from the grid point of view. Thus, parking lots can attain very big capacities.
- For the study to present an interest, we need the infrastructure to exist. It is then reasonable to assume that charging stations have been installed where we need them.

The set of assumptions has the following consequences for our study:

- The storage capability of each BV is a known quantity.

- As our smallest time resolution is the minute, we consider that each BV battery can provide its maximum output instantaneously.

We next consider a collection of B BVs and use the set

$$\mathscr{B} = \{ \ i : i = 1, 2, ..., B \ \}$$

to denote the aggregation. We use a study period of J days for the simulation which we denote by the set

$$\mathscr{J} = \{ \ j : j = 1, ..., J \ \}.$$

The set of days of the study period may include nonconsecutive days as we only consider commute days. Under the assumptions introduced, the commute and departure times and the travel distances of the BVs in the aggregation are variable for each day in the study period. To model the uncertainty, we introduce random variables – RVs – and random processes – RPs.

Definition: the indexed collection of RVs $\left(\underset{\sim}{Y}_t \right)_{t \in \mathscr{T}}$, where $\mathscr{T}$ is an indexed set of times, is said to be a random process. For each t fixed, $\underset{\sim}{Y}_t$ is a standard RV. For each realization y_t of $\underset{\sim}{Y}_t$, y_t is a function of t. We call such a function a sample path of $\left(\underset{\sim}{Y}_t \right)_{t \in \mathscr{T}}$.

The RPs we consider in the modeling are not all defined on the same set of times. We use two levels of time resolutions that we describe schematically in Fig. 3.7.

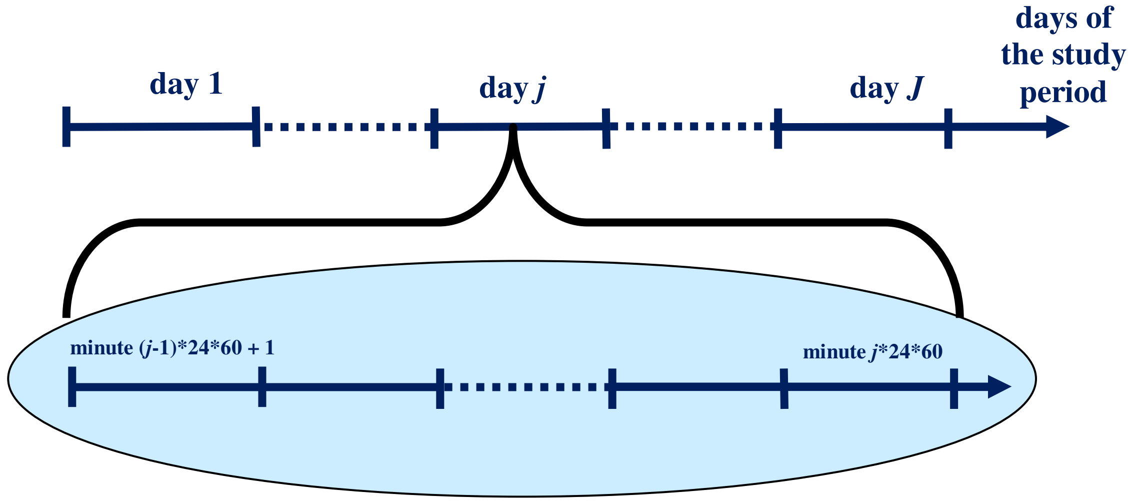

Figure 3.7: The two levels of time resolution in the aggregation modeling

We discuss next the time-independent RPs defined on the set of days of the study period. We introduce the RP $\left(\underset{\sim}{\Delta}^{i,j}\right)_{j\in\mathcal{J}}$ we use to represent the distance traveled by BV i. The distances driven in the morning and in the evening may be different and can then correspond to two realizations of the RV for day j as BV owners may have different itineraries for their forward and return commutes. We denote the RP corresponding to the time at which BV i starts its forward commute by $\left(\underset{\sim}{T}_{f,d}^{i,j}\right)_{j\in\mathcal{J}}$. We also define the commuting time RP $\left(\underset{\sim}{C}^{i,j}\right)_{j\in\mathcal{J}}$ for BV i. Then, we introduce RP $\left(\underset{\sim}{G}^{i,j}\right)_{j\in\mathcal{J}}$ corresponding to the duration of the period during which BV i remains parked during work time. Under our assumptions, the RPs $\left(\underset{\sim}{T}_{f,d}^{i,j}\right)_{j\in\mathcal{J}}$, $\left(\underset{\sim}{C}^{i,j}\right)_{j\in\mathcal{J}}$ and $\left(\underset{\sim}{G}^{i,j}\right)_{j\in\mathcal{J}}$ are independent.

We can get the RP $\left(\underset{\sim}{T}{}^{i,j}_{f,a}\right)_{j\in\mathcal{J}}$ corresponding to the time at which BV i completes its forward commute by doing a summation of the time at which the BV departs for its morning commute and of its commuting time:

$$\underset{\sim}{T}{}^{i,j}_{f,a} = \underset{\sim}{T}{}^{i,j}_{f,d} + \underset{\sim}{C}{}^{i,j}, \forall i \in \mathcal{B}, \forall j \in \mathcal{J}.$$

We can also compute the RV $\left(\underset{\sim}{T}{}^{i,j}_{r,d}\right)_{j\in\mathcal{J}}$ corresponding to the time at which BV i starts its return commute by

$$\underset{\sim}{T}{}^{i,j}_{r,d} = \underset{\sim}{T}{}^{i,j}_{f,a} + \underset{\sim}{G}{}^{i,j}, \forall i \in \mathcal{B}, \forall j \in \mathcal{J}.$$

The time of completion of the return commute is given by the RP $\left(\underset{\sim}{T}{}^{i,j}_{r,a}\right)_{j\in\mathcal{J}}$ defined as

$$\underset{\sim}{T}{}^{i,j}_{r,a} = \underset{\sim}{T}{}^{i,j}_{r,d} + \underset{\sim}{C}{}^{i,j}, \forall i \in \mathcal{B}, \forall j \in \mathcal{J}.$$

We also introduce RPs defined on the set of minutes in order to enable us to determine the ability of each BV to behave as a load or as a generation/storage device in power systems. Such RPs are defined on the time set $\mathcal{M}$ corresponding to the time resolution of minutes.

Contrary to the storage capability k^{i} of BV i, which is a deterministic quantity for the Aggregator as it knows the characteristics of each BV, the amount of energy that is stored in the battery at any point in time is not known a priori by the Aggregator. We define the SOC RP $\left(\underset{\sim}{S}{}^{i}_{t}\right)_{t\in\mathcal{M}}$ for BV i to characterize the ratio of the amount of energy stored in the BV battery at any point in time *t* to the storage capability of the battery. Indeed, the SOC of each BV battery is uncertain to the Aggregator as it depends on the distances traveled by the BV and on the use made of the BV battery as a load or a generation/storage device. The SOC decreases when the BV is being driven or when energy is withdrawn by the Aggregator. It increases when the BV is being charged.

At any minute *t*, we need to know how many BVs are plugged into the grid. In order to know if BV *i* is plugged into the grid at any *t*, we define the RP $\left(\underset{\sim}{\Psi}{}_t^i\right)_{t\in\mathcal{M}}$ by

$$\underset{\sim}{\Psi}{}_t^i = \begin{cases} 1 & \textit{if BV i is plugged in at time t} \\ 0 & \textit{otherwise} \end{cases}, \qquad \forall t \in \mathcal{M}.$$

We have B BVs in our set of BVs. We can then create the total number of useable BVs RP $\left(\underset{\sim}{\Omega}{}_t\right)_{t\in\mathcal{M}}$ representing the total number of BVs plugged into the grid and defined by:

$$\underset{\sim}{\Omega}{}_t = \sum_{i=1}^{B} \underset{\sim}{\Psi}{}_t^i, \qquad \forall t \in \mathcal{M}.$$

For $t \in \mathcal{M}$ fixed, $\underset{\sim}{\Omega}{}_t$ is, therefore, by definition, an integer valued RV whose value lies between 0 and B. The RP corresponding to the total number of useable BVs represents the total number of BVs which are plugged into the grid. However, the Aggregator may not be able to get energy from the plugged in BVs if they have an SOC equal to zero. We define the RP $\left(\underset{\sim}{E}{}_t\right)_{t\in\mathcal{M}}$ representing the total energy stored in the aggregated BVs at any point in time *t* by

$$\underset{\sim}{E}_t = \sum_{i=1}^{B} k^i \underset{\sim}{\Psi}_t^i \underset{\sim}{S}_t^i, \qquad \forall t \in \mathcal{T}.$$

We can similarly define the RP $\left(\underset{\sim}{\Xi}_t\right)_{t\in\mathcal{T}}$ representing the total storage useable by the Aggregator by

$$\underset{\sim}{\Xi}_t = \sum_{i=1}^{B} k^i \underset{\sim}{\Psi}_t^i (1 - \underset{\sim}{S}_t^i), \qquad \forall t \in \mathcal{T}.$$

Under the assumptions previously stated, the random variables – or the random processes at any given point in time – corresponding to different BVs are independent and identically distributed. The central limit theorem then applies to the various RVs describing the aggregation at any point in time. The central limit theorem is usually valid for $n > 30$ [30], a situation which is easily the case for any BV aggregation of interest. As a consequence of this important and fundamental theorem, we can use normal variables to model some characteristics of the aggregation. We can then take $\underset{\sim}{T}_{f,d}^{i,j}$, $\underset{\sim}{G}^{i,j}$, $\underset{\sim}{C}^{i,j}$ and $\underset{\sim}{D}^{i,j}$ to be normal variables for every $i \in \mathcal{B}, j \in \mathcal{J}$.

The problem which appears here is that normal variables are unbounded, which is not the case for some of the RVs defined in our model as shown in Table 3.1. To take into account the bounds of the RVs, we introduce truncated normal random variables.

Definition: The truncated normal distribution is the probability distribution of a normally distributed RV whose values are either bounded below or above – or both.

The derivation of the probability density function and cumulative distribution function of a truncated normal distribution can be found in Appendix A. The RVs $\underset{\sim}{T}\,^{i,j}_{f,d}$, $\underset{\sim}{G}\,^{i,j}, \underset{\sim}{C}\,^{i,j}$ and $\underset{\sim}{\Delta}\,^{i,j}$ for any given j are consequently truncated normal variables.

Table 3.1: Bounds of the RVs

Random variable	Lower bound	Upper bound
$\underset{\sim}{T}\,^{i,j}_{f,d}, \underset{\sim}{C}\,^{i,j}, \underset{\sim}{G}\,^{i,j}$	0	24 h
$\underset{\sim}{\Delta}\,^{i,j}$	0	∞
$\underset{\sim}{S}\,^{i}_{t}$	0	1

To provide simulation results corresponding to the model, we need to use realizations of the various random processes. The sets of realizations are written in the form $\left\{ t^{i,j}_{f,d} : j = 1,2,...,J \right\}$, $\left\{ c^{i,j} : j = 1,2,...,J \right\}$, $\left\{ g^{i,j} : j = 1,2,...,J \right\}$, $\left\{ \delta^{i,j} : j = 1,2,...,J \right\}$.

Furthermore, because of the notion of aggregation, we can take the storage capabilities for an aggregation of BVs to be normally distributed. Such a statement means that the k^{i}s are different realizations of a normally distributed RV $\underset{\sim}{K}$. Once again, such an RV has to be bounded in our model as the storage capability remains in the 0 – 30 kWh range.

From any set of realizations, we can then draw sample paths. Sample paths are important to get an idea of the temporal evolution of a variable. A sample path of $\left(\underset{\sim}{\Omega}_{t}\right)_{t\in\mathcal{H}}$ for $B = 10\,000$ is provided in Fig. 3.8.

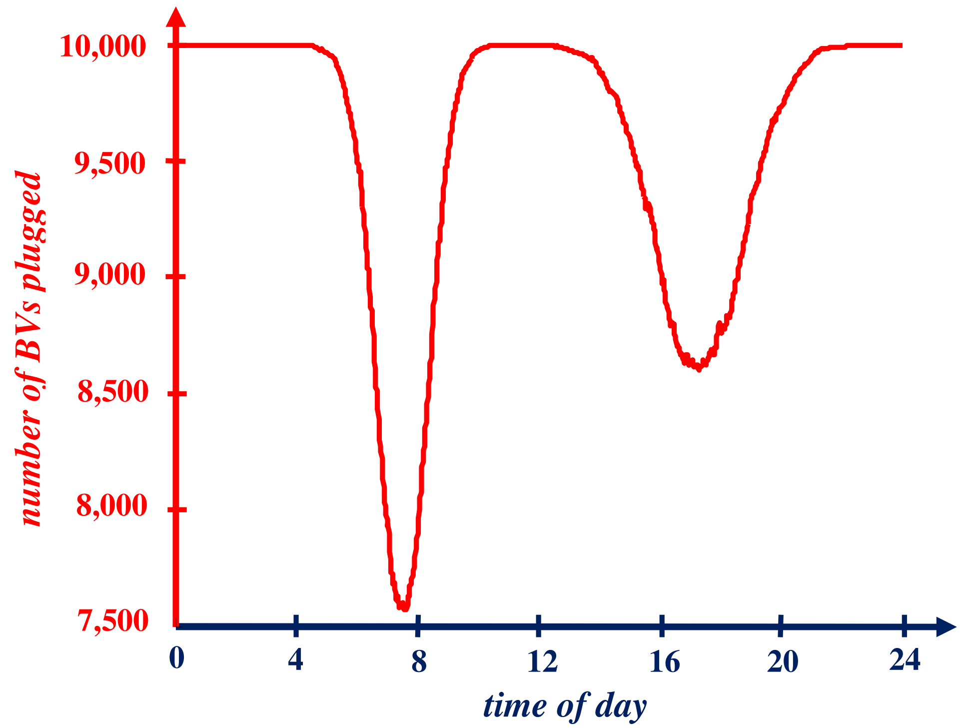

Figure 3.8: Sample path of the total number of useable BVs for B = 10 000

The total number of useable BVs is higher in the evening than in the morning because people leave work over a longer time span. Additionally, the total number of useable BVs remains pretty high even during typical commuting times. The explanation for such a phenomenon is that people have relatively short commuting times on average – around 30 min – and leave at various times in the morning. This is a key finding as it shows that there are always more than 50% of the BVs in the aggregation plugged in at any point in time.

To assess if our model fits the real world situation, we consider a specific parking lot. For this parking lot, we define the number of useable BVs in the lot as the total number of BVs currently plugged in. We compare the result given by the model to actual data for office parking from the city of Livermore, CA [31]. The comparison is provided in Fig. 3.9.

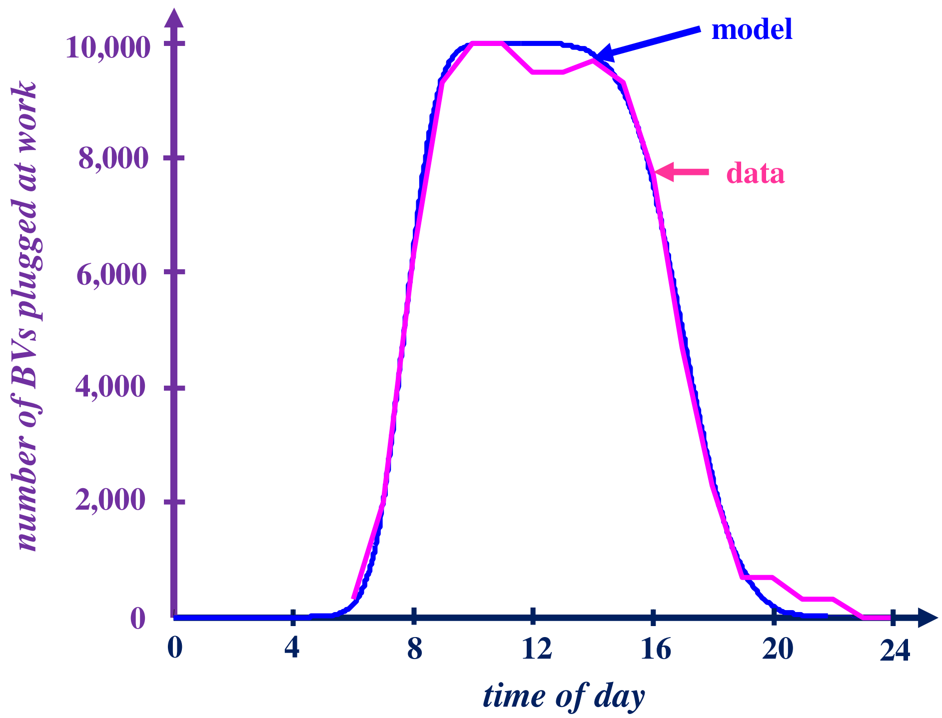

Figure 3.9: Number of useable BVs in a parking lot as a function of time

We observe that the model fits the actual data well, except maybe for the lunch break during which some BV owners take their cars to go to lunch. Indeed, lunch breaks have not been taken into account in our model. Taking such events into account can be done by specifying more subperiods during which the BV is plugged in. However, for the sake of simplicity, such a modification was not performed in this work.

Similarly a sample path of $\left(\underset{\sim}{\Xi}_{t}\right)_{t \in \mathcal{K}}$ for a day is provided in Fig. 3.10. The plots are given for different sizes of the BV aggregation.

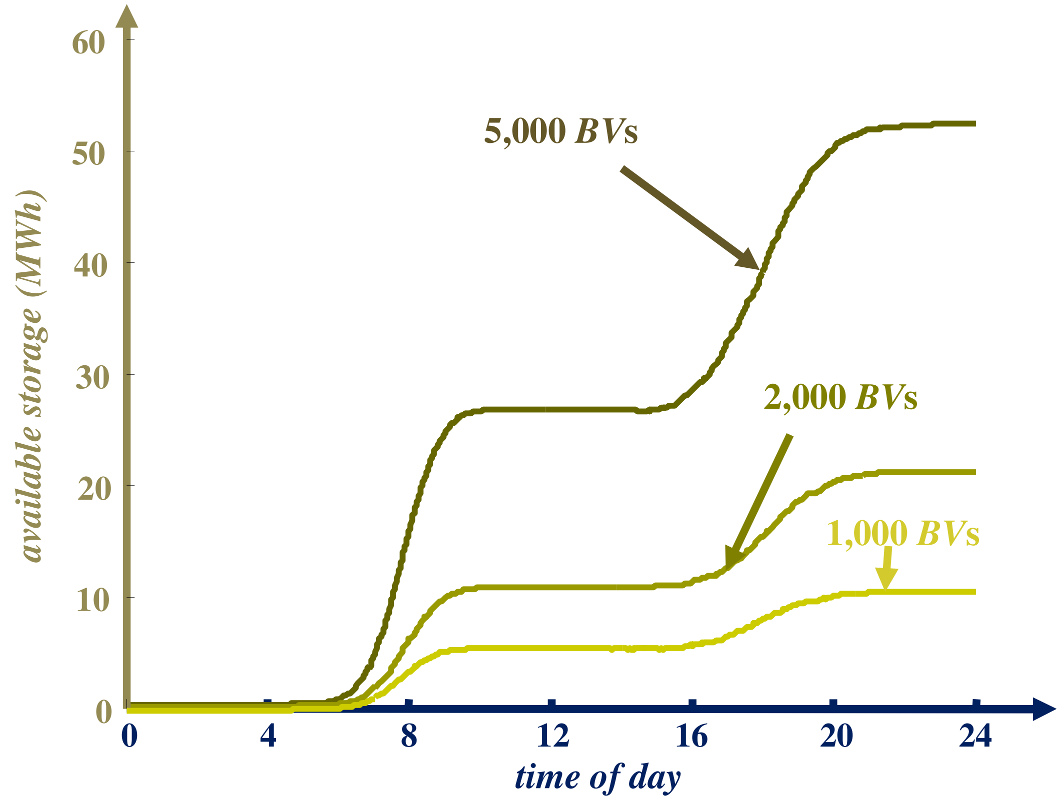

Figure 3.10: Sample paths of the useable storage from BVs for aggregations of varying sizes $1000 \leq B \leq 5000$

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 BVs are not plugged into the grid, a large storage capability – of the order of megawatt-hours – is always available to the grid. The storage capability increases as time goes on because the BVs 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. We will see in Chapter 5 some ways to utilize this storage to improve grid operations.

In this chapter, we have introduced the aggregation concept for BVs. For the BVs to be able to have an impact on the grid, there needs to be an Aggregator that gathers a large collection BVs. With such a collection, the Aggregator can then provide services to the power system by having the BV aggregation play the role of either a controllable load or a generation/storage device. In order to get a better understanding of the effect of the variability inherent on the behavior of the BV owners and on the battery characteristics, we developed a probabilistic model by taking advantage of the large number of BVs in an aggregation and using the central limit theorem. The model provides an accurate way to assess the number of BVs plugged into the grid at any point in time and also the storage available to the Aggregator. The simulation studies in Chapter 5 make extensive use of the model.

4. DESIGN OF A FRAMEWORK FOR V2G

Central to the V2G concept is the integration of the BV aggregation into the grid so that the BVs 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 BVs into the grid is immense. A key need is to develop a conceptual construct or framework whose implementation can bring the V2G vision to reality. We devote this chapter to describing the framework we propose for this purpose.

We start by building the framework after describing the real-world situation. The framework is built on the notion of Aggregation and takes fully into account the BV characteristics. It consists of a physical layer and an information layer. The framework provides the structure for the implementation of V2G. We focus on two key implementational issues: the design of a computer/communication/control network and of an incentive scheme. We propose specific approaches to tackle these implementational needs.

4.1 Proposed Framework

The framework is built taking fully into account the physical characteristics of the BV batteries and the deployment of the BVs. 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 SOC and use it as the determinant for the role each BV can play once plugged into the grid. The Aggregator becomes the key player in making the V2G concept realizable in practical terms. The Aggregator plays the interface role with the BV owners, the ISO/RTO and the ESPs serving the residences of the BV owners. We display in Fig. 4.1 the interrelationships among these players.

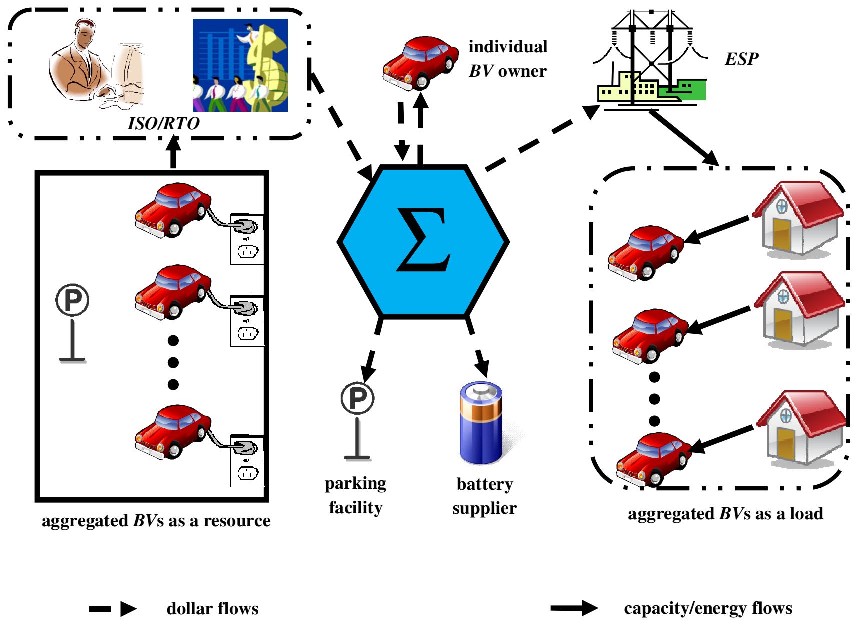

Figure 4.1: The incorporation of the Aggregator into the V2G concept

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 ESPs, 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 as consisting of a physical layer, where the flows are megawatts, megawatt-hours, battery service and parking service, 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. 4.2 to aid us in this examination. The BV aggregation as load receives the electricity supply for charging the batteries from the ESPs that serve the residences of the BV owners. This physical commodity flow is indicated by the MWh links in Fig. 4.2. 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. 4.2. These load and resource services are coordinated through the Aggregator, the central entity that interfaces with the ESPs and the ISO/RTO. In addition, the Aggregator provides the aggregated BVs 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 BVs as part of the collection of services that allow the BVs to be integrated into the grid.

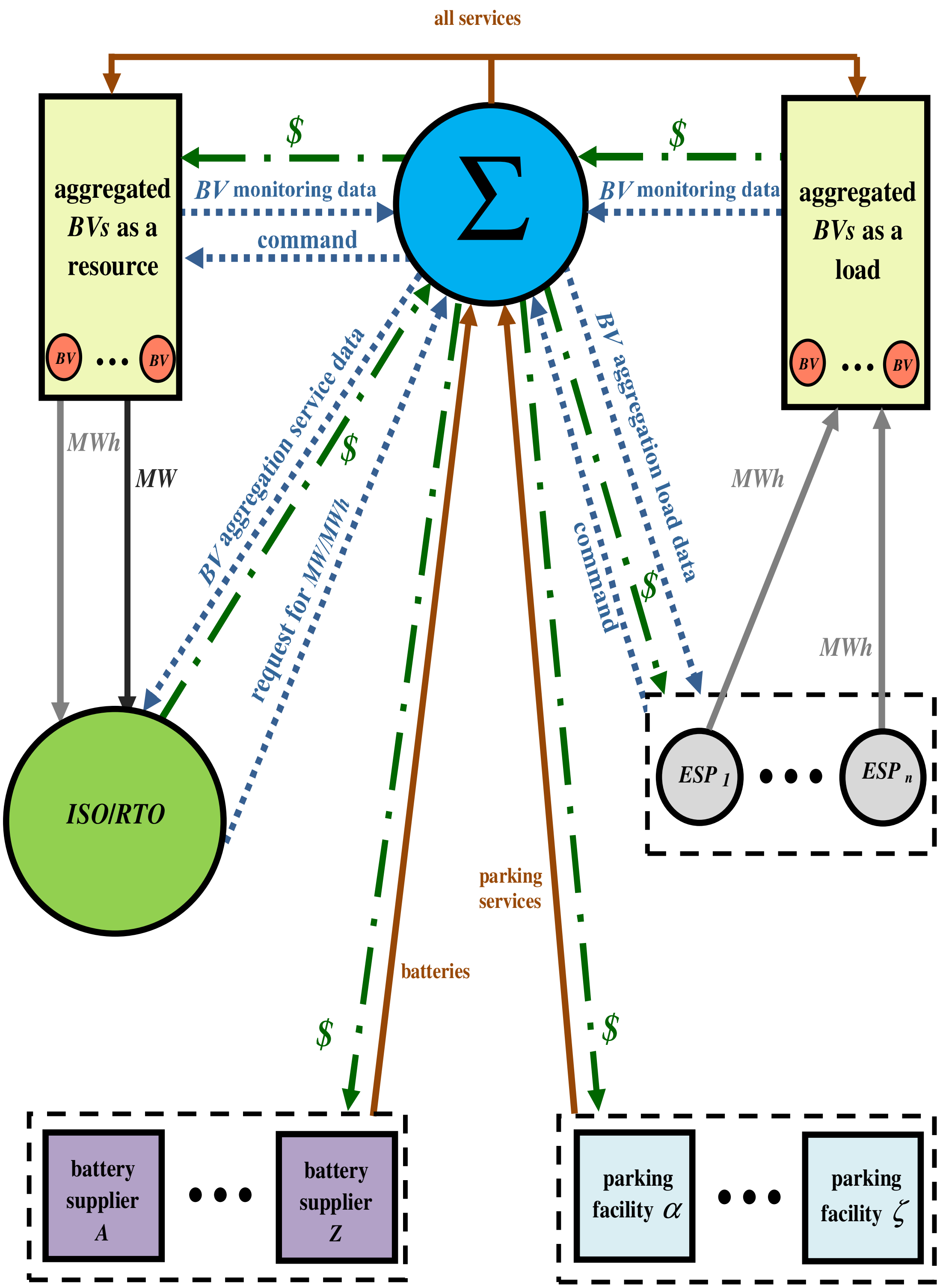

Figure 4.2: The proposed V2G implementation framework

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 megawatt and megawatt-hour services. For the load aggregation of BVs, the Aggregator has bidirectional communications with the ESPs to specify the information needed for the charging of the batteries and for the requirements of load levelization services. The corresponding signals to the BVs are transmitted through the network. In the case of the resource aggregation of BVs, the Aggregator uses the network to convey the needs of the ISO/RTO for capacity and energy services, to identify the subset of BVs 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. 4.2. Conceptually, we also view that the dollar flows to pay for the various services are accommodated by the information layer. The computers that are an integral part of the computer/communication/control system keep track of the set of services that BVs receive from the Aggregator together with the relevant discounts and also the set of services provided by the BVs while parked and interconnected to the grid. The dollar flows are indicated through separate lines in Fig. 4.2. The diagram is shown by collapsing the physical and information flows together to emphasize the extensive interactions among the various components of the 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.

4.2 Steps Towards 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 BVs 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 included. We devote this section to the discussion of the approaches we propose to tackle these two key implementational issues.

4.2.1 Design of a computer/communication/control network

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 bringing the V2G concept to fruition. Specifically, the computer/

communication/control network needs to have the capability to make the required information transfers between the Aggregator and each BV and between the Aggregator and the ISO/RTO and the ESPs. These transfers are bidirectional 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 BVs and the ISO/RTO, keep track of the services provided by the BVs 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 BVs from the ISO/RTO and the ESPs 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 in order to meet the need outlined above. For example, a subnetwork is required at each location where the BVs 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 ESPs. 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 BVs.
- 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 BVs 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.
- 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 4.1 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 ESPs during off-peak conditions at night.

Table 4.1: 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 SOC	percentage	key criterion for BV deployment
power flow from the BV battery to the grid	signed power quantity	required for payments

We show in Fig. 4.3 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 BVs can be plugged in – be it at a parking lot or at a BV owner's residence. The bidirectional ISO/RTO-Aggregator link is used for the information transfer to enable the provision of megawatt and megawatt-hour 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 ESPs to the various locations where the BVs 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 BVs. 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 BVs. Such subnetworks are needed since one is required at each location where BVs can be plugged in.[15]

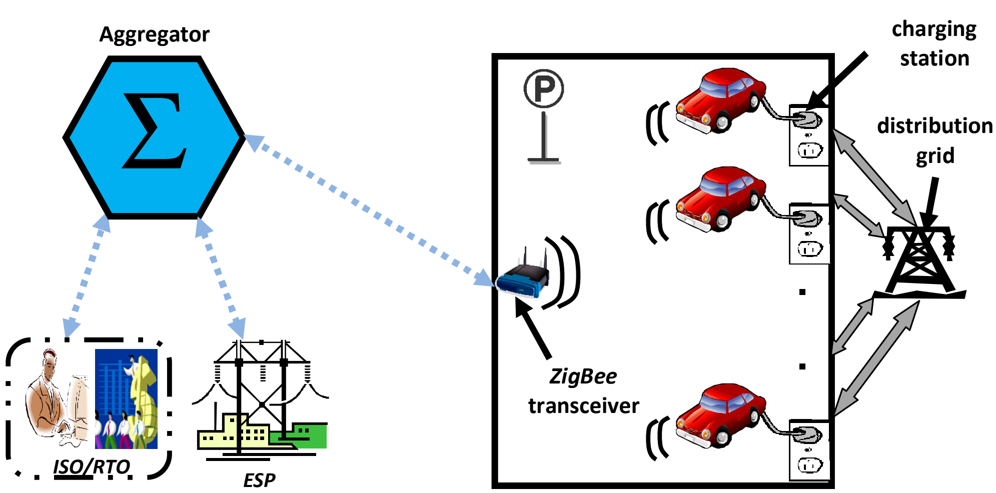

Figure 4.3: Computer/communication/control network for the framework proposed

[15] 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.

Given the multiple interfaces between the various links and the associated subnetworks, the accommodation of analog signals for measuring and monitoring 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 its weakest link.

Virtually all components, with the exception of the local subnetworks, can be implemented using mature technology [32]. However, the local subnetworks which directly link the BVs to the parking lots or the residences require an interface with the smart grid capabilities of the grid [12]. 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 [33].

We investigated the development of a practical approach for the signal transmission in this subnetwork and assessed and compared different technology alternatives.[16] We selected a wireless network with ZigBee[17] 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 cost 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 of 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. 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 [34]. The cyber security aspects of ZigBee have been investigated in power system distribution networks as ZigBee appears to be an important player in demand response applications.[18] The deployment to BVs is rather similar to such networks [36].

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[16] Other technologies which may be considered include Bluetooth and BPL.

[17] 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.

[18] For example, solutions have been developed to have a laptop recharge its battery, or a refrigerator begin its cooling cycle, only when the electricity price is low [35].

4.2.2 Design of an incentive scheme

An equally important challenge is the design of an incentive program to ensure the adequate participation of the BVs in 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. On the other hand, the customers who fail to meet the obligation to plug in their BVs are penalized and receive no discounts at all.

A key cost component in the operation of BVs is that of the battery – its day-to-day maintenance and the costs of its eventual replacement. An Aggregator collecting a large number of BVs 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 interchangeable 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.[19]

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 impact on household monthly expenditures. In addition, because of the provision of battery maintenance and guarantee, BV owners are more inclined to participate and plug in their BVs 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

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[19] 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 [37].

actively in decreasing CO_2 emissions. BVs are viewed as more environmentally friendly than conventional internal combustion cars due to no or lower tailpipe emissions. Indeed, studies indicate that BVs are cleaner even if electricity generation uses fossil fuel sources [38]. In addition, the services provided by the BV aggregation allow the delay of the start-up of old units, thereby decreasing the emissions from older and dirtier plants. The loads due to the charging of BVs during off-peak conditions at night further decrease plant emissions by reducing the need to stop and start 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 depends on the compliance of the BV owners to the obligation 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 guarantee or maintenance services, or the termination of the contract.

The Aggregator signs with every individual BV owner a boilerplate 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 BVs, there is adequately large capacity to be of interest to an ISO/RTO. The services provided by the BVs 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 BVs in the aggregation may be plugged in at locations served by different ESPs, 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 for 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.

In this chapter, we built a framework enabling the implementation of V2G. The framework consists of a physical layer with commodities or service flow and of an information layer with information flows and financial payments. The Aggregator module is the key component of the framework. In order to enable the functioning of the layers of the framework, we focused on two major implementational challenges. We proposed an approach for a computer/communication/control network based on the integration of multiple wireless subnetworks to enable the information flows. We also provided an incentive scheme built around the notion of package deal to enable the attraction and retention of BV owners by the Aggregator.

5. RESULTS OF SIMULATION STUDIES

Our focus in this chapter is on the study of the impacts of the integration of BVs in power systems. We carried out an extensive set of simulations to assess how the integration of BVs into the grid can be helpful in power system operations. In these studies, we explicitly represent the various sources of uncertainty to provide a realistic representation of the real world situation. The simulations indicate that with a large number of BVs in an aggregation, the effects of variability inherent in the BV owners' behavior can be smoothed out. We also investigate the effect of the size of the aggregation on the capability of the BV aggregation to provide the requested services to the ISO/RTO. The performance of sensitivity studies on the size of the aggregation allows the determination of the smallest size of the BV aggregation capable of providing the services requested.

The development of the V2G concept is still in its early stages. Consequently, the amount of data reflective of experience to date is rather limited. For our studies, we make use of public domain data available from various sources. The data come from different locations across the United States. Due to the lack of more extensive data, we may use information extracted from more than a single location for a specific study. In certain cases, where no data are available, we state the assumptions introduced to allow the simulation study to proceed.

In this chapter, we present the results and the discussion of simulation studies in order to provide a concrete illustration of the role played by BVs once integrated into the grid. We start out by investigating the provision of day-time regulation service and energy for load shaving by a BV aggregation and perform sensitivity studies by varying the size of the aggregation. We also investigate how the plug-in of the BVs at night can help to reduce off-peak regulation down requirements. We explore the synergism of the integration into the grid of aggregation BVs with that of wind resources. We provide illustrative results of the effective deployment of the storage that a BV aggregation can provide and the synergistic relationship with the integration of wind power into the grid.

5.1 Daytime Regulation and Load Shaving Services

A highly attractive aspect of the BV integration into the grid is the effective utilization of BVs as a generation/storage device. We present the deployment of BV aggregations of various sizes for the provision of regulation and energy services in this and the next section together with sensitivity studies for variations of the size of the BV aggregation. In this section, the application of interest is the provision of regulation up and down services and the contribution to load shaving. For this study, we use the load in the PJM footprint for a day in summer 2006 and assess the role that an aggregation of BVs can play and investigate the impact of the size of the aggregations.

Corresponding to the load data for June 6, 2006, we use the reserve requirements that are computed by the PJM ISO. We provide the reserve requirements in Fig. 5.1.

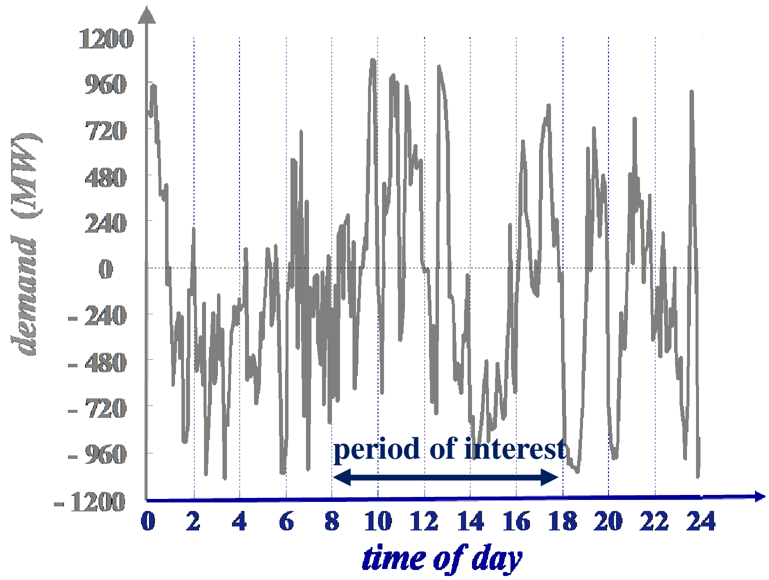

Figure 5.1: The PJM regulation service requirements on June 6, 2006

We assume that all the BV batteries are fully charged before the BVs are driven to work at the beginning of the day. Consequently, all the SOCs are equal to 1. We further assume that each BV battery can maintain a power output at one fifth of its storage capability.

We make use of the probabilistic model described in Section 3.4 with all the associated assumptions. For the aggregation in the study, we assume that all BVs are drawn from the same population in terms of their characteristics. A probability distribution is used for the storage capabilities of the different batteries to represent the fact that all the BV batteries in the aggregation do not have the same storage capability. Indeed, the batteries may have been built by different manufacturers and may be of different vintage and thus probably do not have the same storage capability. We assume that the BVs in the aggregation come from a population that has a truncated normal distribution with mean 20 kWh and standard deviation 5 kWh.

The parameters of the distributions for the departing time, the commute times and the parking times are based on the data collected by the city of Livermore in California [31]. For our study, we assume that, on average, a BV owner starts the commute in the morning at 7:15 a.m. with, on average, a 30 min duration. The BV remains parked for a little more than 9 h before the return commute home. The fact that the commute time can be as large as twice the average commute time under bad traffic conditions is assuming a standard deviation of 15 min. In addition, we assume for this study an average commute distance of 25 km with a standard deviation of 12 km using the data for the city of Livermore. The distribution reflects that the distances may vary from BV to BV and, for a given BV, from day to day. Indeed, some BV owners may take different routes every day if they need to do some shopping or if they want to avoid traffic jams. We summarize in Table 5.1 the parameters assumed for the distributions used in the simulation study.

Table 5.1: Values of the parameters of the probability distributions

r.v.	mean	standard deviation
$\underset{\sim}{K}$	20 kWh	5 kWh
$\underset{\sim}{G}^{i,j}$	9 h 20 min	70 min
$\underset{\sim}{T}_{f,d}^{i,j}$	7:15 a.m.	50 min
$\underset{\sim}{C}^{i,j}$	30 min	15 min
$\underset{\sim}{\Delta}^{i,j}$	25 km	12 km

We start the study with an aggregation of 100 000 BVs for this purpose. The simulation verifies that at each time step during the period of interest, from 8 a.m. to 6 p.m., the BV aggregation has the ability to provide the required up or down regulation service. For each BV battery in the aggregation, the participation is dependent on its SOC – the BV participates in the service provision as long as its SOC value is within the prescribed limits. The provision of the regulation service proceeds along the lines described in Section B.1. For the simulation, we use a time step $\Delta t = 1$ min.

We present the results of the simulation in Fig. 5.2. The simulation provides a good illustration of the ability of the aggregation to provide the 30 MW up and down regulation. We note the bang-bang nature of the regulation provided by the BV aggregation which makes full utilization of the very fast response capabilities of the BV batteries. We also remark that despite the various and uncertain schedules of the individual BV owners, the Aggregator has a collection which is sufficiently large to provide the regulation service throughout the 10 h period. The ability to smooth out such uncertainties comes from the fact that, under the assumptions used, the law of large numbers holds for the BV aggregation considered. Indeed, by the collection of a large number of BVs, the Aggregator can effectively eliminate the impacts of the variability in the BV owners' behavior so as to provide a reliable generation/storage device to the grid.

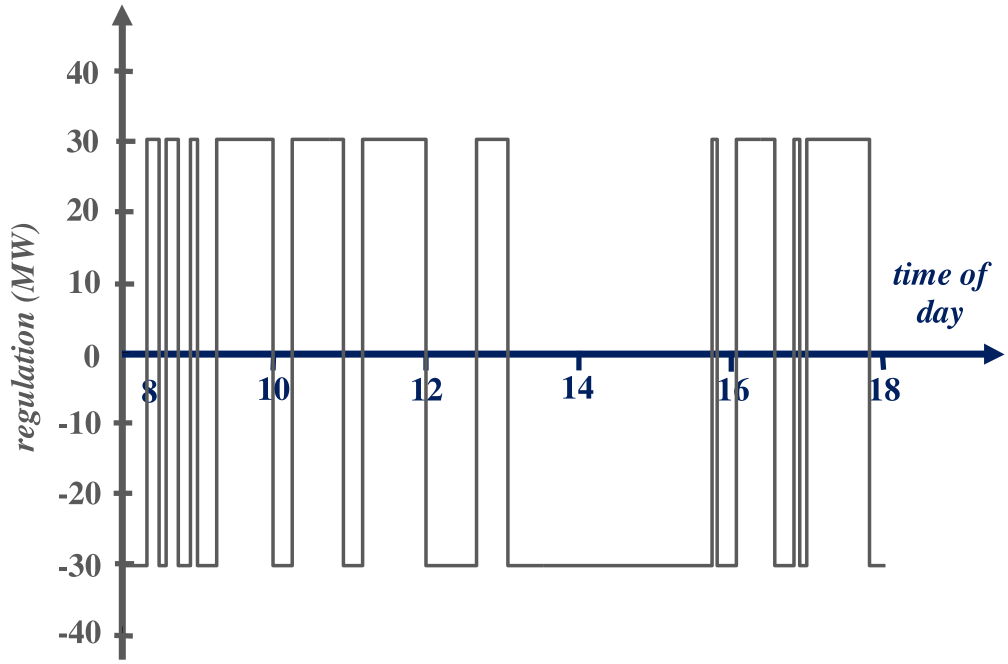

Figure 5.2: The results of the simulation of the provision of daytime regulation service by the 100 000 BV aggregation to contribute to meeting the PJM regulation service

Because the role of a BV in the aggregation depends on the SOC of its battery and because all the BVs are not always connected to the grid, the BVs in the subset of the aggregation that provides the regulation service to the grid may vary. An important index is the fraction of BVs in the aggregation[20] that actually provide the regulation service at each point in time. For this study, we plot this index in percent in Fig. 5.3. We observe that the percentage of BVs which provide the regulation service remains virtually constant. Some of the observed variations may be explained by the difference in storage capability – and consequently power output – from one BV battery to another. Consequently, the number of BVs needed to reach the 30 MW service level may vary

[20] The BVs in the aggregation include the BVs which are currently plugged into the grid and those which are not.

over time. The subset of BVs that provide the regulation up service may be different from that of BVs that provide regulation down service, and the membership of each subset changes in time to reflect that some BVs may no longer be connected or their battery may not have the SOC in the appropriate range to provide the requested service.

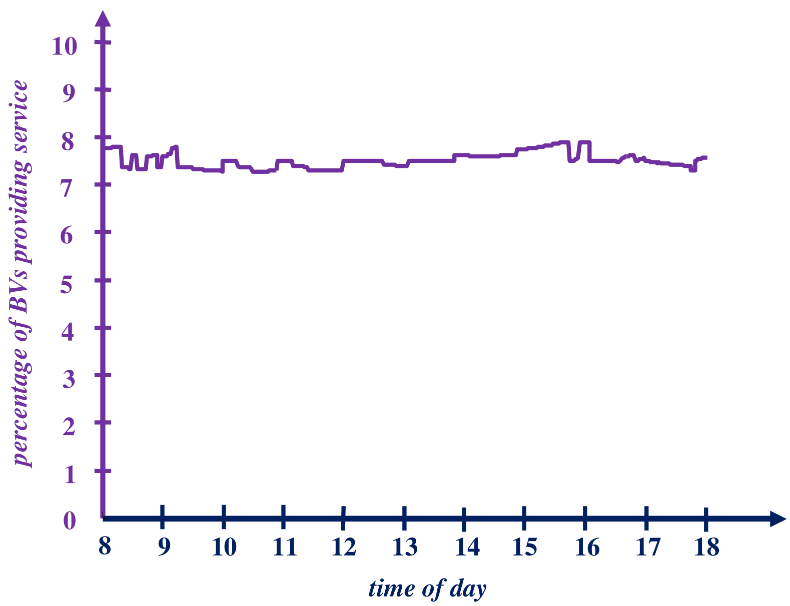

Figure 5.3: Percentage of BVs providing the 30 MW regulation service

We note in Fig. 5.3 that the number of BVs providing regulation service remains rather low, with fewer than 10% of the BVs in the aggregation providing service at each point in time. Consequently, it is reasonable to think that the Aggregator can provide additional services to the grid from the collection of BVs. For example, from the same system and data, we consider the provision of load shaving service in addition to the regulation service. Specifically, the Aggregator needs to provide 100 MWh of load shaving service at a constant power output between 9:00 and 9:30 a.m.. We refer to the Section B.2 for the simulation procedure.

The simulation results with this additional energy service provision indicate that the energy provision can be accommodated. The BV aggregation is able to provide a constant 200 MW output power for a 30 min period in addition to the regulation service which is provided. The provision of regulation service remains unchanged from the first study for regulation service only. We plot the fraction of the BVs that provide the regulation and energy services and the result is shown in Fig. 5.4. We note the huge jump in the percentage of BVs for the short period of time of energy provision, with the other periods very much following the pattern shown for the case of regulation service only in Fig. 5.3. We note than the percentage of BVs providing the regulation and energy services remains below 60% at all times. We explain this observation by the fact that not all the BVs are able to provide service as a generation/storage device because their SOC may be outside the specified bounds. Also, not all the BVs in the aggregation may be plugged into the grid.

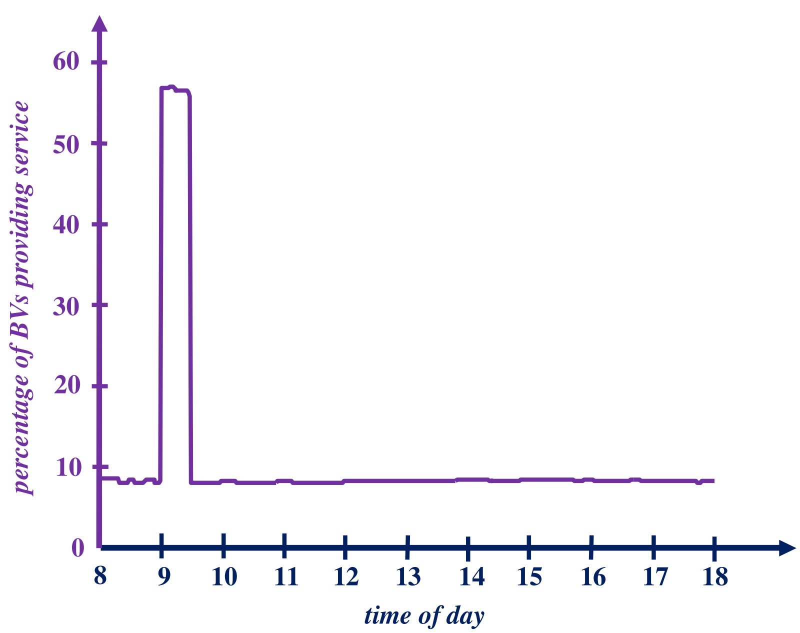

Figure 5.4: Percentage of BVs providing regulation and load shaving service

The plots in Figs. 5.3 and 5.4 indicate that the percentage of BVs providing service remains below 100% and so we investigate whether an aggregation of a smaller size can provide the requested services. For the system under consideration, we repeat the study with a decrease in the number of BVs in the aggregation. The results indicate that for a 2% decrease in the size of the aggregation, i.e., an aggregation of 98 000 BVs, the provision of the 200 MW output over the 30 min period is no longer possible. The Aggregator either reduces the duration of service – the provision of 200 MW output over 25 min is possible – or reduces the output level and still provides the energy service over a 30 min period. The provision of the regulation service meets no difficulties for the 98 000 BV aggregation. As the number of aggregated BVs decreases, we observe the maximum constant power output for energy services for the 9 – 9:30 a.m. period. For instance, for a collection of 85 000 BVs, the Aggregator can provide at most an 85 MWh load shaving service with a constant power output at 170 MW for the 30 min period. When the aggregation reaches 43 000 BVs, the collection can no longer provide any energy in addition to the 30 MW regulation service over the 10 h period. When it reaches 40 000 BVs, the 30 MW regulation service can no longer be provided. The sensitivity results for the size of the aggregation are given in Fig. 5.5.

We note that, while, at any point in time, fewer than 8000 BVs are needed to provide the regulation as shown in Fig. 5.3, the aggregation needs to be considerably larger for the service provision to continue uninterrupted over the 10 h period. The provision of the additional energy service pushes the size of the aggregation to be larger to allow the provision of both services for the given day.

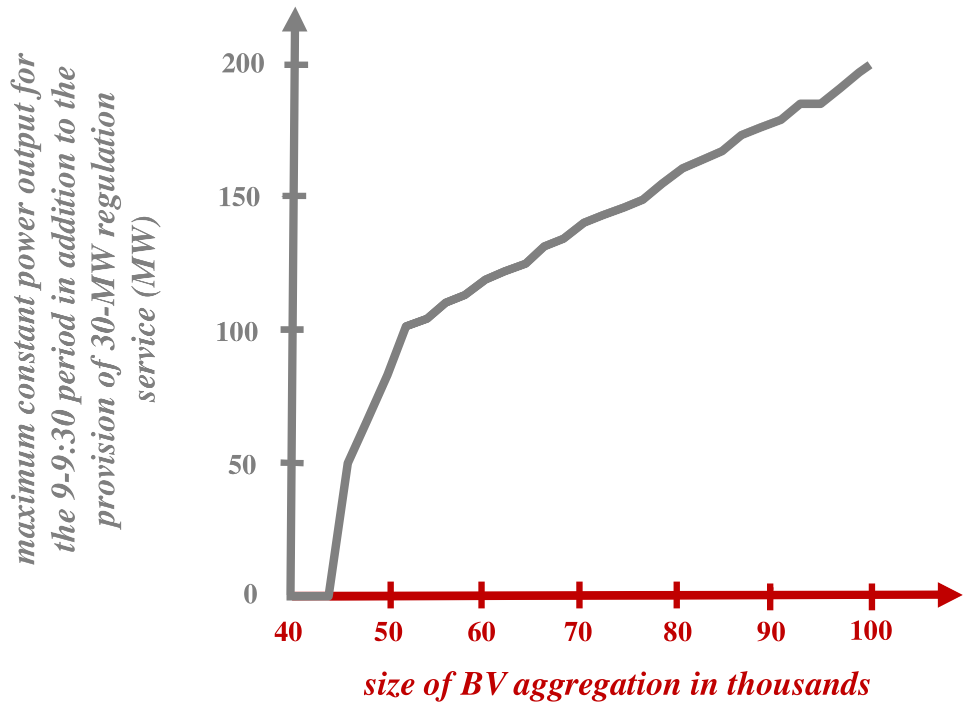

Figure 5.5: Maximum constant 30 min power output a BV aggregation can provide in addition to the provision of 30 MW regulation service as a function of the aggregation size

The simulation studies discussed in this section shed light on the impacts of BV aggregations of different sizes on the ability of the Aggregator to provide regulation and energy services to the power system. The results clearly show the ability of BV aggregations to provide significant regulation service and important amounts of energy for load shaving purposes. Furthermore, we show the desired effect of aggregation in smoothing the variability due to the BV owners' behavior and the BV battery characteristics. However, the aggregation has to be large enough to cope with the fact that some BVs may no longer be plugged in into the grid or that some BV batteries may no longer have their SOC in the desired range to be able to provide the requested services.

5.2 Nighttime Regulation Service

BV aggregation can also be used during the time the BVs are plugged in at the homes of the BV owners. Possible applications include load levelization and reducing regulation down requirements. We focus in this part on the ability of BV aggregations of different sizes to provide regulation down service at night. The regulation down requirements are, typically, very acute during the off-peak period. The load is low and the ISO must pay entities to decrease the generation or to increase the load. We show here how aggregations of BVs can decrease regulation requirements at night – from midnight to 6 a.m. – by increasing the load.

We make the important assumption that the BVs do not get charged before the beginning of the period in which we are interested. The other assumptions for the simulation are the same as in Section 5.1. The assumption on the charging period is justified by the fact that charging before midnight is not economically interesting. We make use of the probabilistic model described in Chapter 3. The parameters chosen for the parameters of the distributions are the same as in Section 5.1. Consequently, each BV comes back at the end of the day with an SOC that may be different from that of another BV as the distances they drove may be different. Because of the parameters chosen for the time distributions of the probabilistic model, more than 99% of the BVs in the aggregation are plugged in at any time during the simulation period.

We use the data of off-peak regulation requirements from the PJM ISO for June 6, 2006, shown in Fig. 5.6. In the simulation, the BVs are used to provide the regulation service requested by the PJM ISO. We refer to Section B.3 for more details on the simulation procedure. Δ t is taken to be 5 min here. We repeat such a procedure for aggregations of 10 000, 50 000, 100 000 and 500 000 BVs. Results are presented in Fig. 5.7.

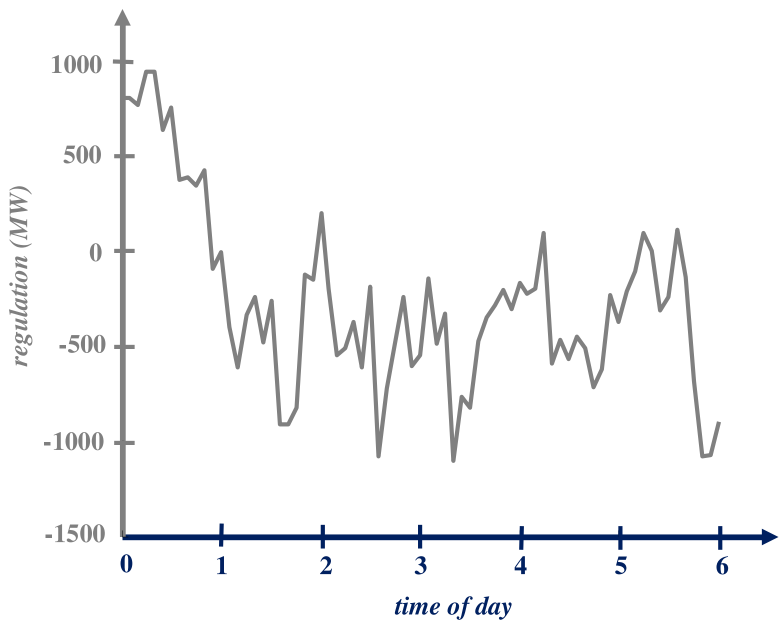

Figure 5.6: Off-peak regulation requirements for PJM for June 6, 2006

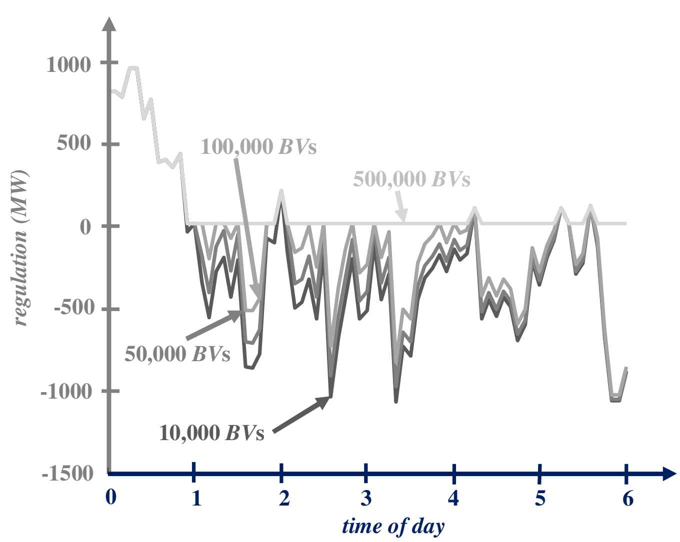

Figure 5.7: Regulation requirements with 10 000, 50 000, 100 000 and 500 000 BVs

We observe that the effect of an aggregation of 10 000 BVs on regulation requirements is hardly visible. After a few hours, the BV batteries are full and there is no more storage capability from the BVs that can be used by the grid. Thus, the Aggregator cannot provide any additional load to the system to decrease regulation requirements. We have the same phenomenon with 50 000 BVs even if the effect is more perceptible. The regulation down requirements are decreased a little but not on the whole period. The situation becomes much more interesting with 100 000 BVs. With such an aggregation, the regulation requirements are decreased by a significant amount – almost 300 MW – over a long period – at least 4 h. With 500 000 BVs, the regulation down requirements for the off-peak period are considerably decreased over the whole period. We reach a state in which the number of BVs plugged into the grid is high enough to annihilate the regulation requirements. The consequence of such a situation is that the generation output of the current system has to be increased to ensure that all the BVs can get charged.

In this section, we analyze the impacts of BV aggregation on the off-peak regulation requirements for the PJM system. The results clearly indicate the role collections of BVs can play in increasing the load and reducing regulation requirements. Once again, we were able to show the crucial importance of the size of the BV aggregation by noticing that the larger the size of the aggregation, the more important the role the Aggregator can play in the power systems area.

5.3 Integration of BVs and Wind Energy

We discuss here a case study to investigate the synergies between wind energy and BV integration into the grid. The integration of wind energy into the grid is another big challenge for the grid operators. The intermittency represents a major drawback of the wind technology as it introduces a lot of uncertainty in the power output of a wind farm. We want to assess the role BV aggregations can play in facilitating the integration of wind resources into the grid. The goal of the study is to use the storage capability provided by the BV batteries to levelize the power output of a wind farm. The BVs can get charged using the wind power output and act so as to levelize it.

The simulation makes use of the probabilistic model developed in Chapter 3 to take into account the variability introduced by the BV owners' behavior and the BV characteristics. We assume the same values for the parameters of the distributions as in Section 5.1. We also particularize the study to PHEV aggregations to take advantage of the internal combustion engines they carry on board.

We do not model the uncertainty in wind power here as it is not in the scope of the thesis. Instead, we use actual data from Aberdeen, ID [39], which is a location in which winds are strong enough to present the potential for the installation of wind turbines. Figure 5.8 provides us with the wind speed on an entire 7 day period for the specified location.

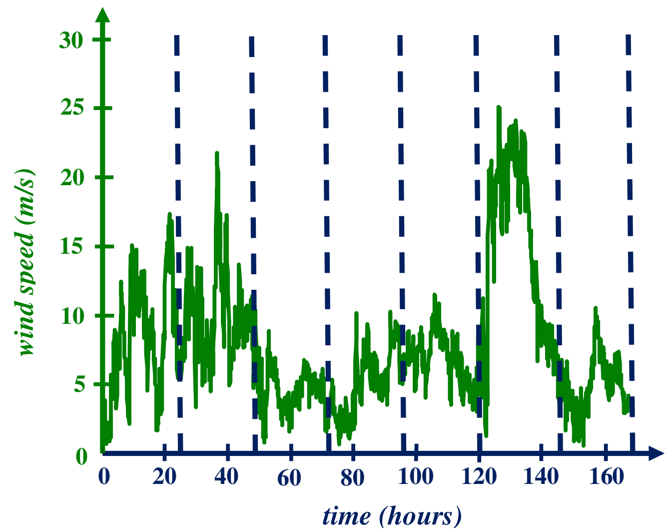

Figure 5.8: Wind speed for a 7 day period in Aberdeen, ID

We note that the wind speed is highly variable over the selected weeklong period from nearly 0 to over 25 m/s. From wind, power can be generated using wind turbines. The characteristics of wind turbines and the wind farm selected for the study are given in Section C.1. For the chosen wind farm, we construct in Fig. 5.9 the wind power output curve as a function of time.

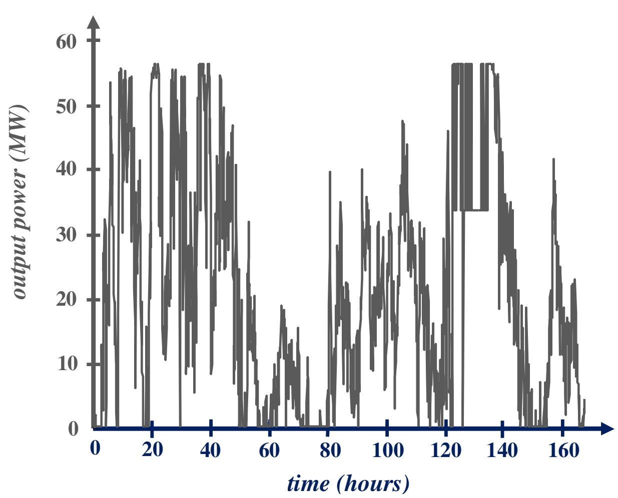

Figure 5.9: Example of wind power with a 56 MW wind farm for a 7 day period in Aberdeen, ID

We note in Fig. 5.9 that the power is very intermittent. We also note the presence of phases during which the power reaches its maximum value – 56 MW – and of periods during which the output power of the wind farm is zero. The presence of periods with zero output power represents an important challenge for the ISO/RTO as it does not know if it can rely on such energy resources. The integration of a PHEV aggregation with the wind farm can be effectively harnessed by levelizing the wind farm output. If the power output of the wind farm is flat, it becomes much easier to integrate the wind farm in the power system as its output is no longer uncertain.

For the study, we consider a system formed of the 56 MW wind farm, a grid and B aggregated PHEVs as depicted schematically in Fig. 5.10.

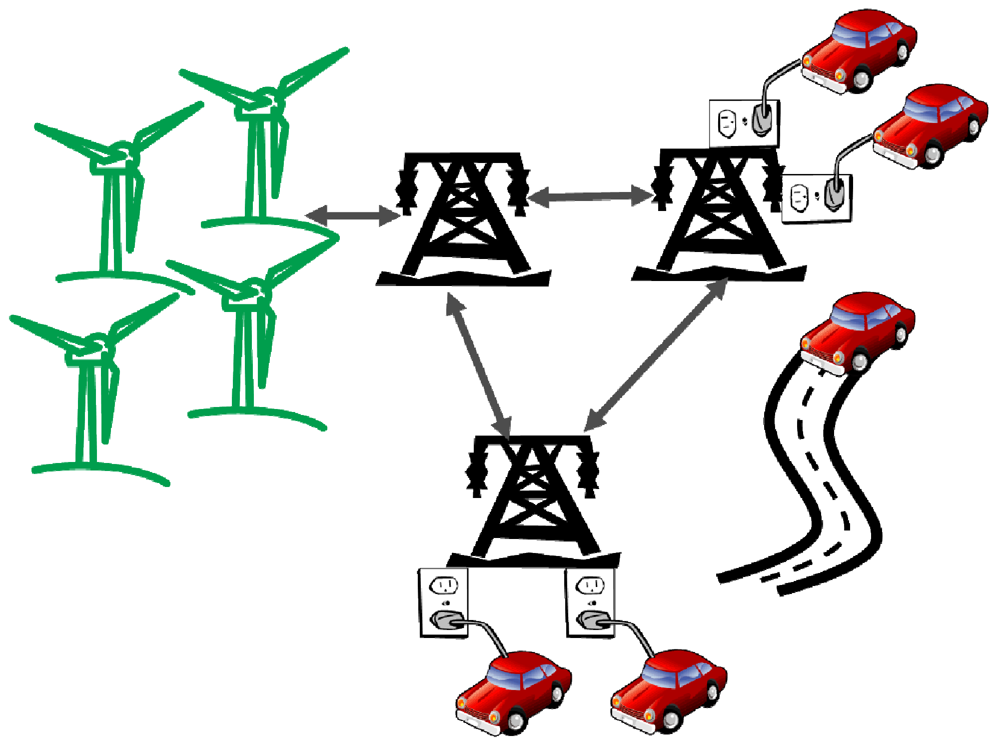

Figure 5.10: Study system formed of a wind farm, transmission lines and aggregated PHEVs

The simulation is performed over a 7 day period. We want to find the maximum levelized power output attainable on the study period and the associated number of PHEVs. We increase the wind output by sending power from the aggregated PHEVs, and we decrease it by sending power to them. The simulation procedure is detailed in Section C.2. The goal of the procedure is to have a constant wind output ω^s over time for the wind farm by sending or withdrawing energy from the aggregated PHEV batteries. We take here $\Delta t = 1$ min and $\Delta \omega = 1$ MW. For the wind signal given before, we find a solution to the problem for $\omega^s = 7$ MW and $B = 44\,000$.

The simulation shows that it is possible to attain a levelized power output for the wind farm. The numbers of 44 000 PHEVs and 7 MW were found using the wind power output levelization procedure. The value of the levelized power output is much lower than the maximum capacity of the wind farm for two main reasons. The wind power output is highly intermittent, so the wind farm rarely produces electricity at its rated power. Also, PHEVs in the simulation use the electricity produced by the wind turbines for their commuting needs and thus the levelized power output is the power output obtained after charging the PHEVs. By levelizing the wind power output of the wind farm, the PHEV aggregation decreases the variability around the behavior of the wind farm. The ISO/RTO knows that, with a PHEV aggregation of sufficient size and despite the variability inherent to both the wind and the behavior of the PHEV owners, it can obtain a constant output for the wind farm and thus rely on it at any time without fearing the periods during which the wind does not blow.

We want to see what happens with fewer PHEVs. Indeed, if the Aggregator collects fewer PHEVs, the amount of storage capability useable by the grid is smaller but the total energy needed for the propulsion of the PHEVs is also smaller. We can see the effect of the size of the aggregation by considering what happens for 20 000 PHEVs only. Such a case is depicted in Fig. 5.11.

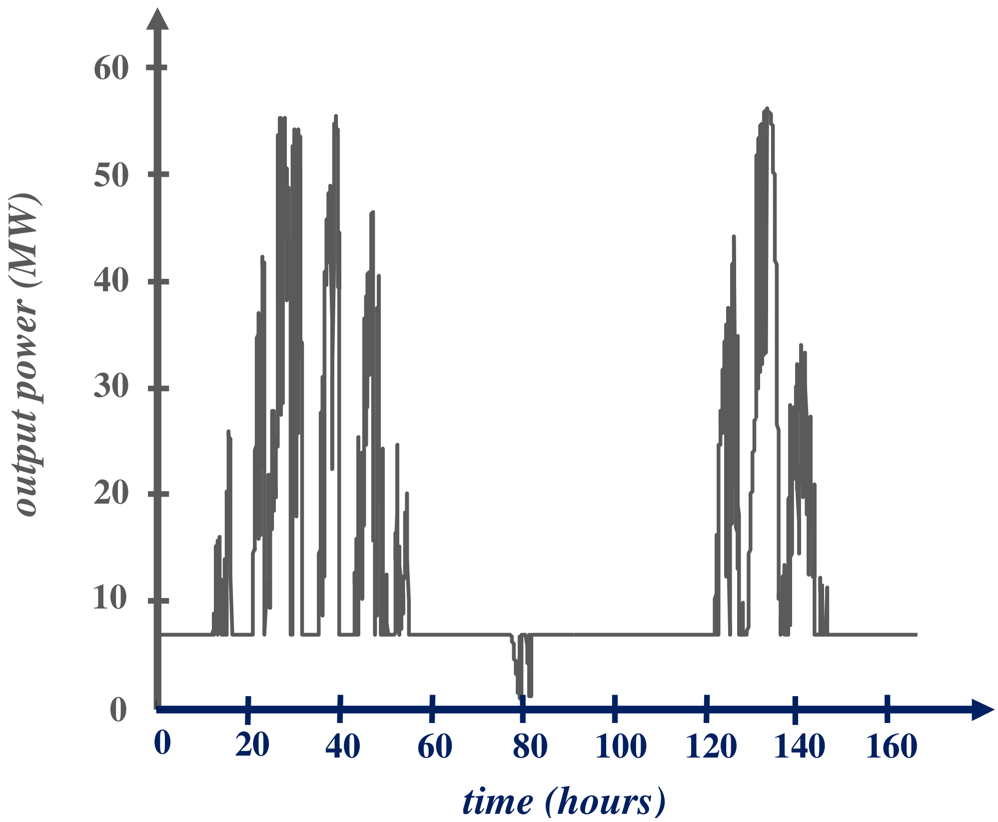

Figure 5.11: Modified wind power output for a 7 MW level and 20 000 PHEVs

In this case, we observe two distinct phenomena. For some periods, the output power is higher than the specified output power. The reason is that there is not enough storage capability from the PHEV batteries plugged into the grid to absorb this excess in energy. Either the PHEV batteries are full or the aggregated PHEVs are not plugged into the grid. In some parts of the curve, the output is lower than the desired power level. There is not enough energy stored to provide the necessary energy to the grid. Such a case shows that there is not enough storage useable by the grid and, thus, that the

Aggregator has not assembled a collection of BVs which is sufficiently large to levelize the output of the considered wind farm.

We also study a case in which the specified levelized output is higher with the same aggregation of 44 000 BVs. An example is provided in Fig. 5.12 which shows the output for a specified power level of 10 MW.

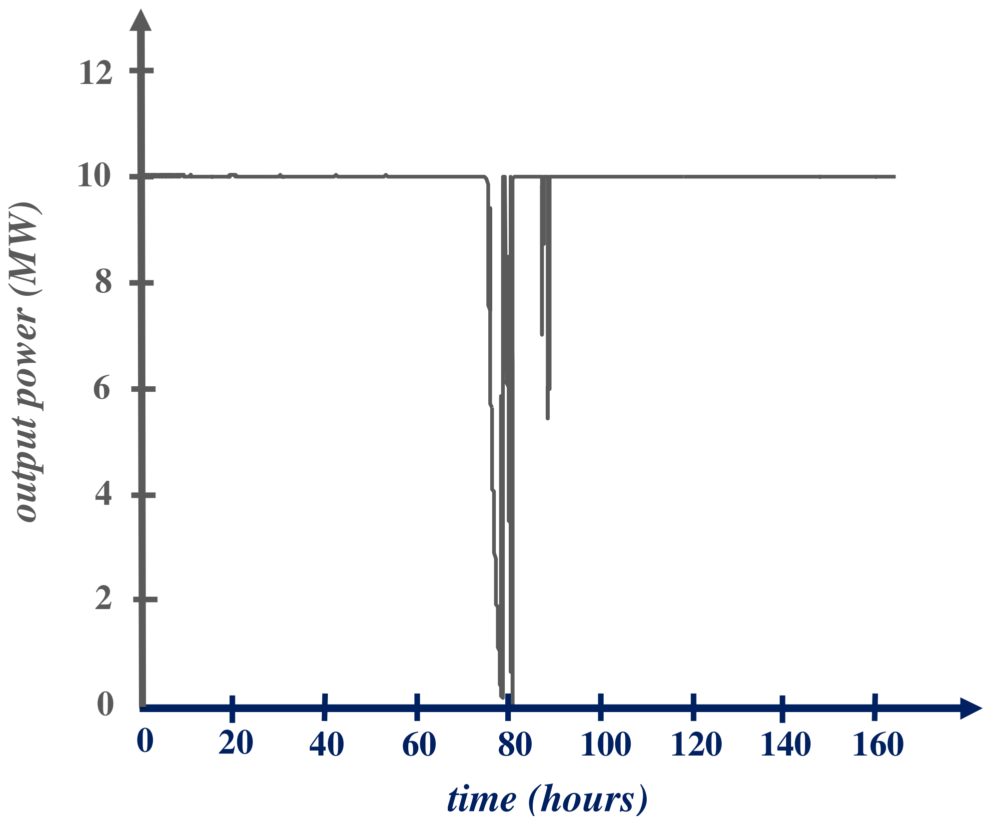

Figure 5.12: Modified wind output for a 10 MW level and 44 000 PHEVs

During the period corresponding to low wind speeds – from hour 78 to hour 83 – there is not enough energy stored or enough capacity to reach the necessary power level. We note that increasing or decreasing the number of PHEVs does not solve the problem in this case. Lowering the number of PHEVs decreases the useable storage capability and, consequently, the PHEV aggregation is not able to provide the power needed at hour

78 because there is not enough energy stored in the PHEV batteries. If the number of PHEVs is increased, there is no longer enough energy produced by the wind farm to charge the PHEVs and maintain the constant power output. To find a solution, the specified power level needs to be decreased, as is done in the levelization procedure.

We have shown in this section the synergistic relationships between a PHEV aggregation and a wind farm with both integrated into the grid. We also described a method to find, for a collection of BVs, the maximum levelized power output which can be attained. The designed tool can be used to assess, for different wind farms, the sizes of the BV aggregations needed to levelize the output. The tool can also be used for operations in order to determine when to store energy in the BV batteries and when not to.

5.4 Concluding Remarks

We reported the results of our simulation studies for different applications of BV aggregations interconnected to the grid. We focused on showing how BV aggregations can facilitate power system operations and provide useful services despite the uncertainty around them. We found that there is a considerable potential for the BVs to provide frequency regulation services by taking advantage of their very fast response capabilities. We also noted that a considerable amount of energy can be provided by the BV batteries to the grid for short periods of time so as to provide load shaving services. BVs can also be used to dramatically reduce regulation down requirements at night by providing a controllable load to the system. Also, the integration of PHEVs into the grid has a synergistic relationship with that of wind power. The storage provided by the aggregated PHEVs enables the grid operator to cope with the intermittency inherent to wind power by providing levelization means.

We also showed the crucial impact of the size of the BV aggregation. Gathering many BVs enables the aggregator to smooth out the effect of the variability inherent in BV owners' behavior by taking advantage of the law of large numbers.

6. CONCLUSION

In this thesis, we present the development of a proposed framework for the implementation of the V2G concept. Throughout the thesis, we explicitly point out the crucial role of BV aggregations. We investigate the roles they can play in power systems as controllable loads or as a generation/storage device. We build a conceptual framework with two layers to enable the implementation of V2G. We also propose specific approaches for two of the most critical implementational challenges by providing a design for a computer/communication/control system and for an incentive scheme. We report simulation results for different applications of the integration of BVs into the grid to study the effect of uncertainty and quantify the services the Aggregator can provide.

The framework shows the range of services the BVs, 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 BVs to form aggregations and dealing with ESPs 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 ESPs or the ISO/RTO and the individual BVs. By explicitly taking into account the physical characteristics of the BVs, the framework provides sufficient flexibility to be used for operations and planning purposes. In order 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 BVs as well as between the Aggregator and the ESPs 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 for the BV owner's obligation to plug in the BV at specified times.

The modeling we developed for BV aggregation allows us to quantify the storage available to the grid from the BVs at any point in time. The model takes into account the variable schedules of the BV owners and the fact that the distances they drive may vary. The simulation results we reported have shown the critical role of the BV aggregation in smoothing out the uncertainty related to V2G. For large aggregations, the Aggregator can provide regulation or load shaving service for a long period of time despite the fact that all the BVs may not be always plugged into the grid and that they may need energy for transportation. We also provided an illustration of how BVs can act as a load by considerably reducing regulation down requirements at night. However, once again, we noted that the size of the aggregation is a critical variable for the Aggregator to be able to play an important role in power system operations. We have also shown that the integration of BVs into the grid has strong synergistic relationships with that of wind power. Indeed, aggregation of BVs can provide storage to the grid which enables the power system to smooth out the power output of a wind farm despite the variability inherent in the behavior of the BV owners, the BV characteristics and the wind speed.

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 BVs 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 BVs 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 promoting further BV penetration in a responsible manner.

APPENDIX A: THE TRUNCATED NORMAL DISTRIBUTION

In this appendix, we develop the mathematical characterization of the truncated normal variables used in the modeling of BV aggregations.

A.1. Definition of a Truncated Normal Variable

Definition: Let $\underset{\sim}{X}$ be a normal variable with mean μ and variance σ^2

$$\underset{\sim}{X} \sim \mathcal{N}(\mu, \sigma^2)$$

which lies within the interval (a, b)

$$\underset{\sim}{X} \in (a, b), -\infty < a < b < \infty.$$

Then the random variable $\underset{\sim}{Y}$ defined as $\underset{\sim}{X}$ conditional on $a < \underset{\sim}{X} < b$ has a truncated normal distribution with probability density function

$$f_{\underset{\sim}{Y}}(y; \mu, \sigma; (a, b)) = \begin{cases} \dfrac{\frac{1}{\sigma}\phi(\frac{y-\mu}{\sigma})}{\Phi(\frac{b-\mu}{\sigma}) - \Phi(\frac{a-\mu}{\sigma})} & if \quad y \in (a, b) \\ 0 & if \quad y > b \ or \ y < a \end{cases}$$

and cumulative distribution function

$$F_{\underset{\sim}{Y}}(y; \mu, \sigma; (a, b)) = \begin{cases} 0 & if \quad x < a \\ \dfrac{\Phi(\frac{y-\mu}{\sigma}) - \Phi(\frac{a-\mu}{\sigma})}{\Phi(\frac{b-\mu}{\sigma}) - \Phi(\frac{a-\mu}{\sigma})} & if \quad a < x < b \\ 1 & if \quad x > b \end{cases}$$

where ϕ is the probability density function of the standard normal distribution $\mathcal{N}(0,1)$ and Φ its standard cumulative distribution function.

Examples of the plots of cumulative distribution functions of truncated normal variables are given in Fig A.1. We note in Fig. A.1 that the derivative of the cumulative distribution function is clearly not continuous in the points *a* and *b*. Such a result comes from the expression of the probability density function of truncated normal variables that present discontinuities in *a* and *b*.

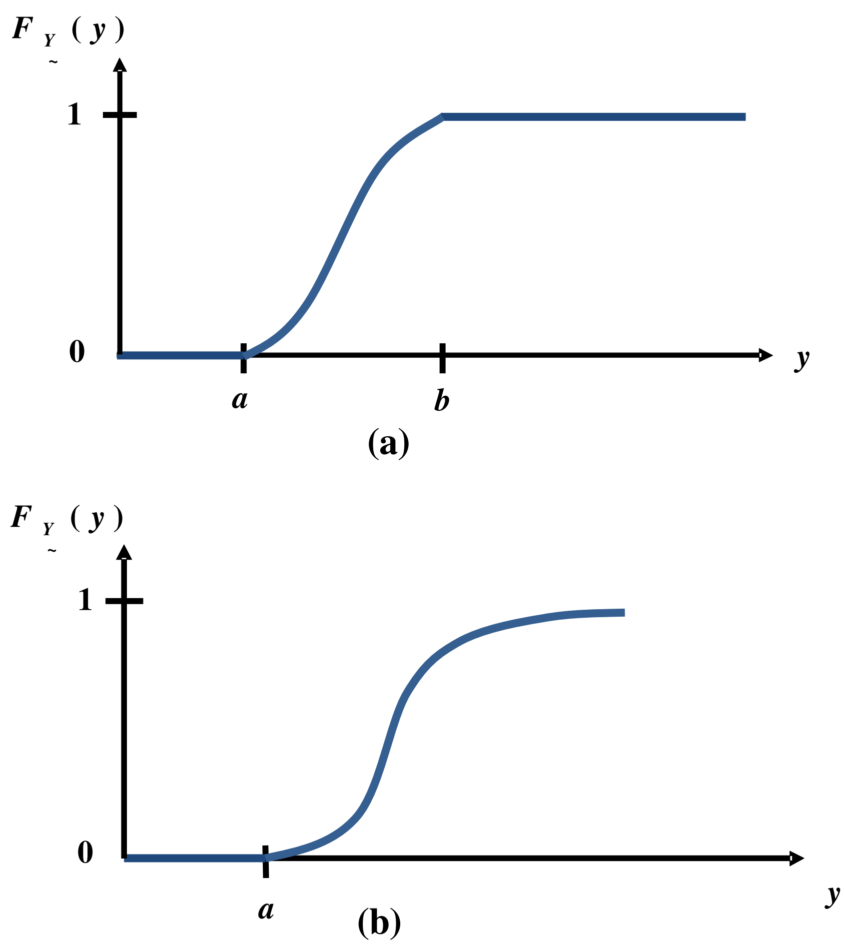

Figure A.1: Cumulative distribution function of a truncated – two-sided (a) and one-sided (b) – normal random variable

A.2 Derivation of the Cumulative Distribution Function

The expression of the cumulative distribution function of a truncated normal variable comes from the use of conditional probabilities.

We have for every $y \in \mathbb{R}$

$$F_{\underset{\sim}{Y}}(y) = F_{\underset{\sim}{Y}}(y;\mu,\sigma,a,b) = P\{\underset{\sim}{Y} \leq y\} = P\{\underset{\sim}{X} \leq y \mid \underset{\sim}{X} \in (a,b)\}.$$

Thus, we can write

$$F_{\underset{\sim}{Y}}(y) = \frac{P\{\underset{\sim}{X} \leq y \ \cap \ \underset{\sim}{X} \in (a,b)\}}{P\{\underset{\sim}{X} \in (a,b)\}}.$$

And we know that

$$P\{\underset{\sim}{X} \in (a,b)\} = \Phi(\frac{b-\mu}{\sigma}) - \Phi(\frac{a-\mu}{\sigma})$$

and we can easily get the expression of the probability of the event

$$\{\underset{\sim}{X} \leq x \ \cap \ \underset{\sim}{X} \in (a,b)\}:$$

$$P\{\underset{\sim}{X} \leq y \ \cap \ \underset{\sim}{X} \in (a,b)\} = \begin{cases} 0 & \text{if} \quad y < a \\ \Phi(\frac{y-\mu}{\sigma}) - \Phi(\frac{a-\mu}{\sigma}) & \text{if} \quad a < y < b \\ \Phi(\frac{b-\mu}{\sigma}) - \Phi(\frac{a-\mu}{\sigma}) & \text{if} \quad y > b \end{cases}$$

Consequently, we get the expression given in Section A.1.

A.3 Special Cases

The truncated normal variable need not be truncated on both sides. We note that

$$\text{if } b \to \infty \text{ then } \Phi(\frac{b-\mu}{\sigma}) \to 1$$

and that similarly

$$\text{if } a \to -\infty \text{ then } \Phi(\frac{a-\mu}{\sigma}) \to 0.$$

Therefore, we find the probability density function of a normal random variable in the case $a \to -\infty$ and $b \to \infty$. In our model, the variables may be truncated either on only one side or on both, depending on the bounds shown in Table 3.1.

APPENDIX B: SIMULATION PROCEDURES

In this appendix, we present the simulation procedures which we use for the provision of up and down regulation service and load shaving service.

B.1 Provision of Daytime Regulation Service

In the first part of the simulation, we want the BV aggregation that has been assembled to provide 30 MW regulation service from 8 a.m. to 6 p.m.. The BVs provide regulation up service when they send power to the grid and regulation down service when they absorb power.

The first step in the simulation is to determine the regulation requirements

$$\{ r_t : t = 1, ..., 660 \}.$$

The r_t are computed using the actual regulation requirements r_t^{ISO} from the PJM ISO by

$$r_t = sign(r_t^{ISO}) * \min\{ 30, | r_t^{ISO} | \}.$$

Then, at every time *t*, depending on the need for regulation up or down, we form the subset of the BVs that can provide the needed service. In order for a BV to provide a service, it has to be plugged into the grid and the SOC of its battery has to be between the adequate limits. We refer to Section 2.2 for the explanation of how a BV can be selected for a given application as a function of the SOC of its battery.

Now that we have formed the adequate subset, we can calculate the regulation service that can be provided by “iterating” on the BVs in the subset. Once we have reached r_t, we stop and update the time $t = t + \Delta t$. If there are not enough BVs to reach

r_t, we stop the simulation and increase the number of BVs in the aggregation. A flowchart of the procedure is provided in Fig. B.1.

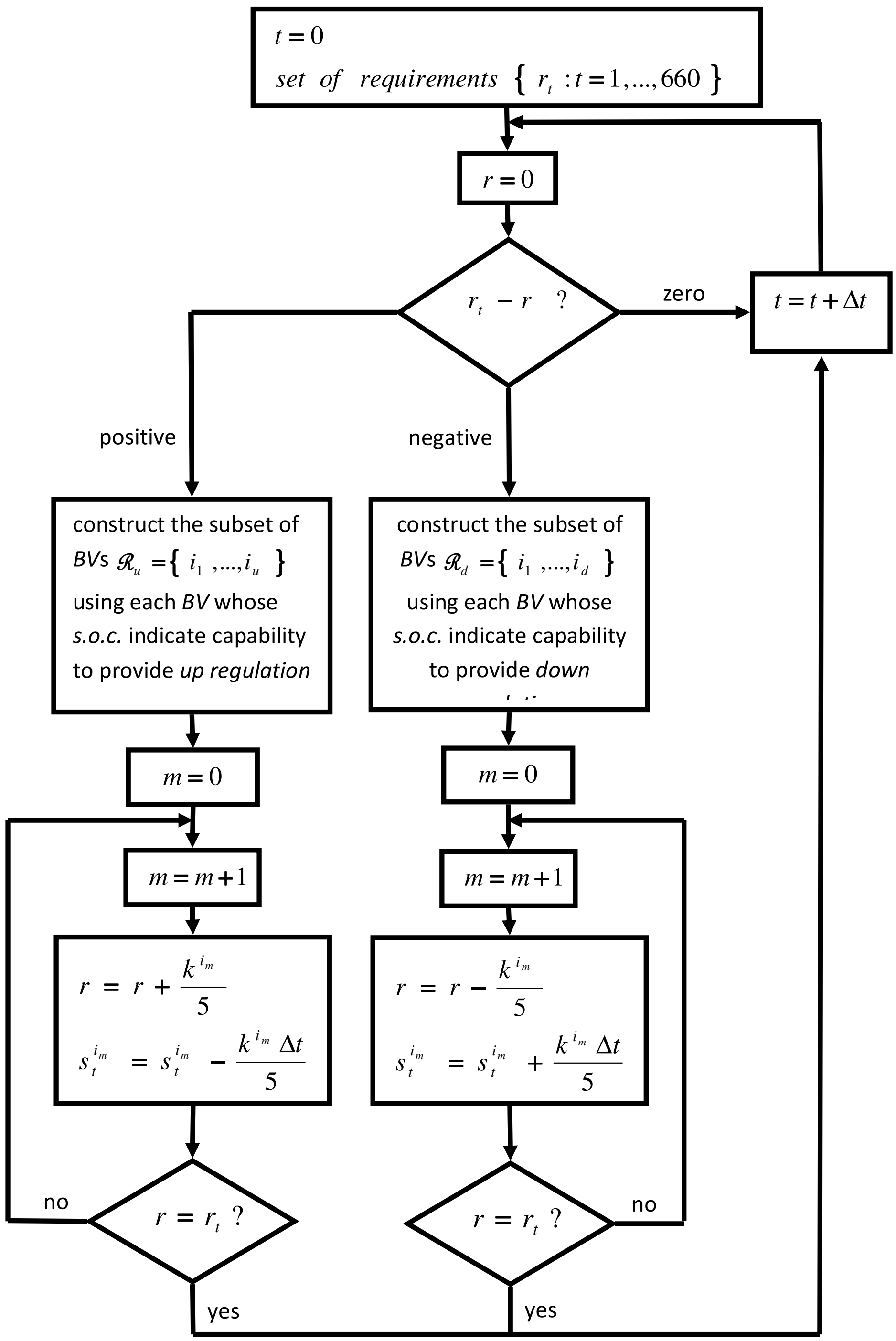

Figure B.1: Flowchart of the procedure for the provision of daytime regulation service

B.2 Provision of Additional Load Shaving Service

The provision of load shaving service is performed in addition to the provision of regulation service. The procedure described in Section B.1 remains unchanged. The difference with the previous section is that we also want to get a constant power output from the BV aggregation for a 30-min period.

We start by specifying the desired power level for the constant power output. At every time t, we construct the subset of the BVs which can act as a generation/storage device and are not already participating in the provision of the regulation service. If the desired power level can be attained with part or all of the BVs in the subset, we set the power output at time t to this value and decrease the SOC of each BV providing the service based on its storage capability. Once we have done so for every BV, we increase t. If this is not the case, we start over with a lower desired power level. We repeat this decreasing procedure until the power output can be provided at the desired level or until we reach a zero-value for the desired level of power output.

B.3 Provision of Nighttime Regulation Service

The simulation is performed between midnight and 6 a.m.. We want to use the BVs to reduce the regulation requirements on this period. The procedure is similar to that described in Section B.1 except that the r_t are equal to the regulation requirements by the PJM ISO. We construct the subsets in the same way as in Section B.1 and compute the modified regulation requirements due to the charging of the BVs.

APPENDIX C: SIMULATION OF WIND FARM OUTPUT AND INTEGRATION

C.1 Wind Turbine Characteristics

Various wind turbines are available on the market from two main manufacturers – GE and Vestas. Despite this variety, all turbines have similar power curves. We give in Fig. C.1 the shape of a typical wind power curve for a turbine g_γ and define its main parameters:

- θ_{in}^{γ}: cut-in wind speed. It is the minimum wind speed necessary for the turbine to produce any power.
- θ_{out}^{γ} : cut-out wind speed. It is the wind speed above which the turbine is turned off and does not provide any more power.
- ω^{γ}: rated wind power. It is the maximum power the wind turbine can produce.
- θ_{r}^{γ}: rated wind speed. It is the wind speed at which the wind turbine first reaches its rated wind power ω^{γ}.

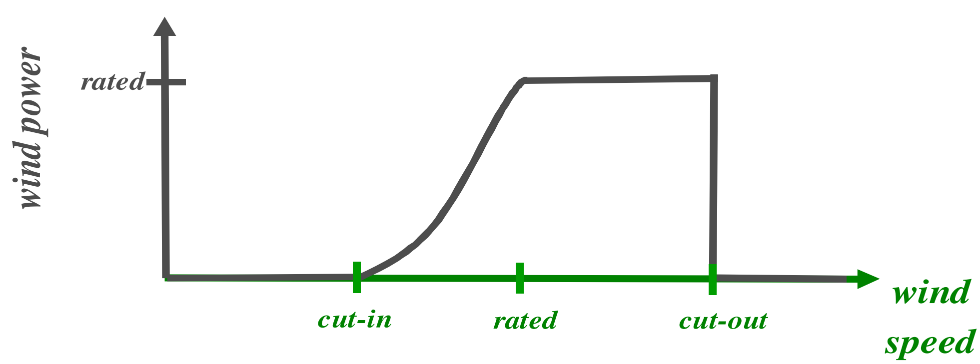

Figure C.1: Typical wind power curve

Instead of considering a single wind turbine, we take a 56 MW wind farm whose characteristics are described in Table C.1.

Table C.1: Wind farm characteristics

turbine	cut-in speed (m / s)	cut-out speed (m / s)	rated wind speed (m / s)	number
GE 1.5 MW	3.5	20	12.5	15
GE 2.5 MW	3.5	25	12.5	10
Vestas 850 kW	4	25	16	10

C.2 Simulation Procedure

The objective of the simulation is to obtain a flattened power output for the wind farm. We start the simulation with a given number of BVs and choose a desired constant power output level ω^s that we want the wind farm to deliver over the simulation period. We also need to retrieve the set of wind power output for the study period. The simulation is performed on a study period of several days, and we update the values of the different variables every Δt.

At every time t, we consider the subset of the BVs plugged into the grid. In case the power output of the wind farm is higher than the desired power level, we use the BVs in the subset of the useable BVs that have an SOC enabling them to play a load role. The SOC of each individual BV in the subset is increased accordingly and the power output of the wind farm is decreased. If the power output of the wind farm is lower than the desired power level, we use the BVs that can play a generation/storage device role to increase the power level. We iterate on the appropriate subsets of BVs. If we reach a state in which the power level of the wind farm output is equal to the desired value, we stop the iterations and go to time $t = t + \Delta t$. If this is not the case, we decrease the desired power level and start the simulation again from the initial time. A flowchart of the simulation procedure is provided in Fig. C.2.

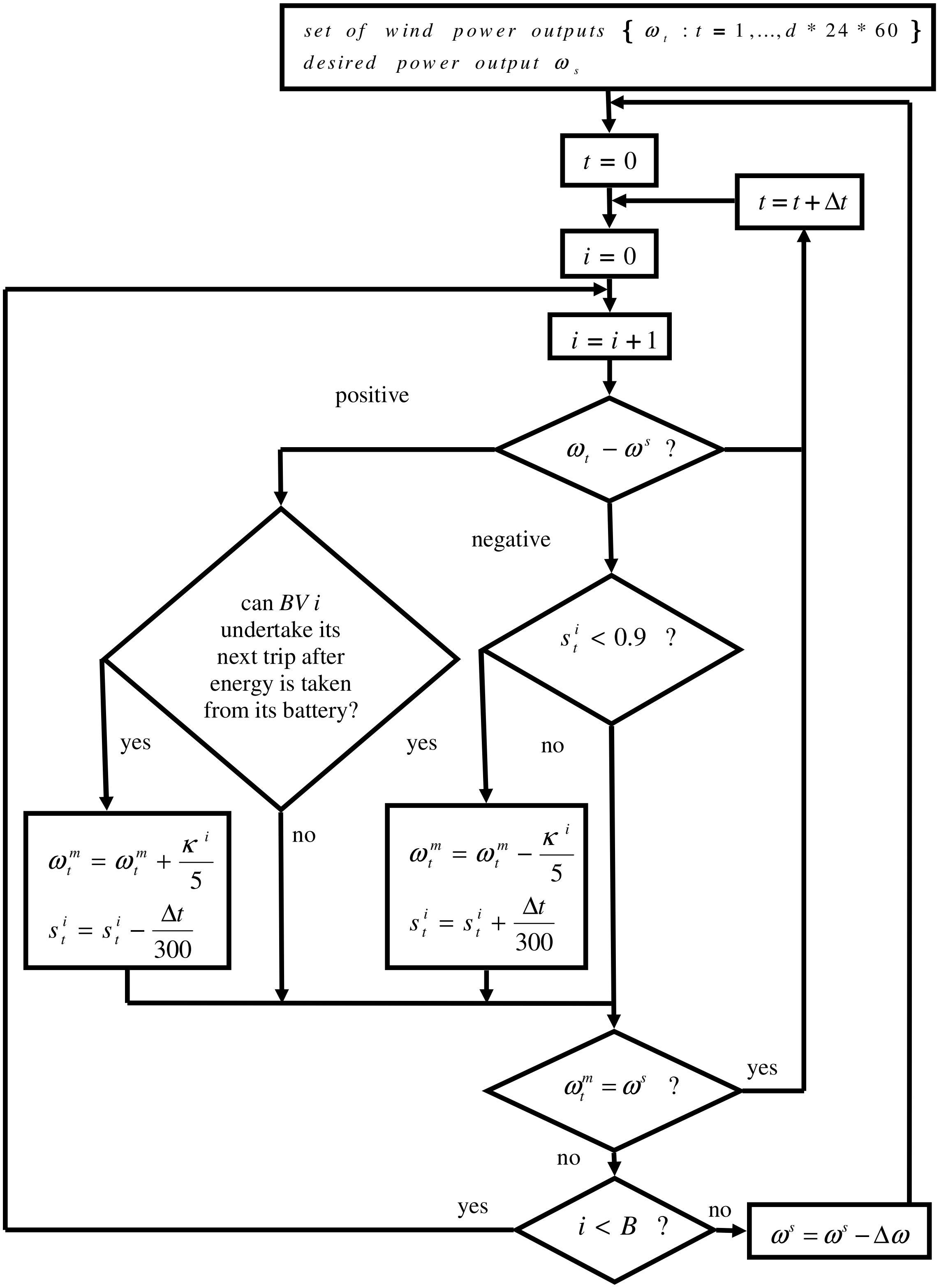

Figure C.2: Flowchart of the wind output levelization procedure

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