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Economic and technical management of an electric vehicles aggregation agent: a literature survey

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SUMMARY

The foreseeable increase in the use of electric vehicles (EV) led to the discussion about intermediate entities that could help manage a great number of EV. An aggregation agent for electric vehicles is a commercial middleman between a system operator and plug-in EV. For the system operator perspective, the aggregator is seen as a large source of generation or load, which could provide ancillary services such as spinning and regulating reserve. Generally these services will be provided in the day-ahead and intraday electricity markets. In addition, the aggregator also participates in the electricity market with supply and demand energy bids. This paper provides a comprehensive bibliographic survey on the aggregator role in the power system operation and electricity market. The scope of the survey covers 47 references divided in journal, conference proceedings, thesis, research papers, and technical reports published after 1994. These papers are put into several technical categories: electricity market and EV technical and economic issues; aggregation agent concept, role and business model; algorithms for EV management as a load/resource.

KEY WORDS: Aggregation agent, electric vehicles; electricity market, ancillary services, vehicle-to-grid.

1 INTRODUCTION

The synergy between power system and electric vehicles (EV) became an important issue for several actors, e.g. vehicles industry, electrical utilities and regulators. For instance, according to Kempton *et al.* [1] the mechanical power of the U.S. light vehicle fleet exceeds the electric power generation of the country by a factor of 24. The same authors [2] show that just one-fourth of the US light vehicles converted to EV would have a power capacity above the electric generation system (660 GW against 602 GW).

In this paper the acronym EV comprises vehicles powered by batteries, a fuel cell, or a hybrid combining a gasoline engine with a generator. Chan *et al.* [3] present an overview of the state-of-the-art for these three vehicle types with emphasis on architectures and energy management models.

Research on this topic was developed in the last decade, in particular the economic and technical problems related with the integration of EV on the electrical network and electricity markets. The vehicle-to-grid (V2G) concept was introduced in 1997 by Kempton *et al.* [4]. Under this concept, the electrical network could receive power from a parked EV, and in this case the charger is bidirectional (able to deliver power to the grid and also to charge the battery). This concept enhances the former paradigm where the vehicles were merely additional loads for charging batteries [5].

The authors associated to V2G the services of peak power and storage for increasing the benefits to electrical utilities, in addition to a raise in profits due to an increase in electrical energy consumption and generation units' load factor. Furthermore, V2G could increase the openness of electrical utilities to renewable generation, but if EV are charged during peak hours additional conventional generation units would be required to meet this additional demand.

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Kempton *et al.* [6] assuming a maximum electrical plug capacity of 15 kW computed the potential power of V2G for several countries. For example: in Portugal, 5.8 millions of vehicles would lead to 87 GW, for an average load of 5 GW; Germany, with 44.6 million of vehicles has a potential of 670 GW, for an average load of 58 GW.

Brooks *et al.* [7] mentioned that the V2G concept does not necessarily means that the power flow must come from the vehicle to the grid. Vehicles only with the unidirectional charge that can be controlled are also providing V2G services. In this unidirectional charge the EV is capable of controllably reducing or increasing consumption under dispatch control signal and responds proportionally to frequency changes (operates as a grid controllable load). Quinn *et al.* [8] have a different opinion: V2G is when the EV has the ability to provide electrical energy to the network, and the Grid-to-vehicle (G2V) is when the network provides electrical energy to the plug-in EV.

One of the main requirements and challenges to make feasible a massive penetration of plug-in EV is to design a framework for management and operation attached to the smartgrid paradigm [9][10]. Under this framework the aggregation agent for EV plays an important role as a commercial middleman between a system operator (SO) and compound plug-in EV. Load aggregators are not new actors in the electricity market. It is common to have regulated and non-regulated aggregators that buy electrical energy at wholesale price and sell at retail price to several costumers. Nevertheless, EV aggregation agents are more elaborated, primarily because they can offer more services and technical flexibility than a simple load aggregator, and EV is a distributed resource that can create technical challenges and opportunities on the distribution network. Note that with the increasing levels of distributed generation in the distribution grids, it is also foreseen in the literature the emergence of distributed power generation aggregators [11].

The aggregator, from the SO perspective, is seen as a large source of generation or load, which could provide ancillary services such as spinning and regulation reserve. The aggregator may contract the ancillary services directly with the system operator, but generally these services will be provided in the day-ahead and hour-ahead electricity markets. Furthermore, the aggregator can participate in the electricity market with supply and demand energy bids, or perform an optimized coordination with renewable energy power plants to create a win-win situation for generation companies (e.g. decreasing forecasting errors) and system operators (e.g. avoiding bottleneck situations in the grid).

It is foreseen that the EV aggregation agent activity will be included in future laws and regulations for the electricity sector. For instance, in Portugal the recent Decree Law nº39/2010 [12] establishing the main lines for the massive integration of EV considers the figure of an electricity retailer for charging EV. Moreover, the position paper of the consulting firm Oliver Wyman [13] foresees the emerging of non-utility companies, which can either became partners or disruptors of utilities business models. Electrical energy storage, smart metering and charging points were identified as the most relevant business opportunities across the value chain and which can shape this emerging market.

The aim of this literature survey is to give an overview about the economical and technical value of EV and the importance of having an EV aggregation agent for both system operators and EV owners.

The paper is organized as follows: section 2 presents the state-of-the-art about the economic and technical issues of EV in the electricity market; section 3 presents the aggregator concept and business model according to several authors; section 4 describes the algorithms developed by several authors to deal with EV in the power system; finally, section 5 presents the conclusions.

2 EV Economic and Technical Issues in the Electricity Market

In average each vehicle is parked a large number of hours per day. During this time a plug-in EV can create additional value to the owner by supporting the electrical power system with several services sold in the electricity market by an aggregation agent. This section presents a literature survey about the services that an EV (and thus an aggregator) can provide to the power system and sell in the electricity market.

2.1 Peak and Base Power

Kempton *et al.* [4] in 1997 computed for the first time the economic value of three types of EV (differing in battery type, battery cost and potential output) as peak power resource. The authors compared EV supplying peak power to the electrical network with an existing utility program, residential Direct Load Control (DLC). The results show that the EV solution offers the same investment cost but five times or more the peak support capability of the DLC program. The authors also computed the monthly cost to the EV owner of providing to the local utility access to its battery storage system. In these calculations the battery wear cost due to charge-discharge cycle dominates other costs such as cost of recharge electricity and losses in charging. The results show that the typical demands savings, which is the monthly demand charge that utilities charge their commercial and industrial costumers for the peak power, is more than the double of the monthly cost for the EV owner.

The authors also computed the levelized avoided capacity cost to represent what a utility is willing to pay for additional capacity. A comparison was performed between the annual cost to the EV owner by annual number of discharges and the annual value to utility of EV peak power capacity. The results showed that under several possible scenarios (different avoided costs and number of discharges) it can be cost-effective for a utility as well as for the EV owner. For instance, an EV owner could provide power at a net present cost of $910 while the net present value to utility is $3900. Finally, the authors mentioned that the utility could offer several incentives to the EV owner, such as vehicle purchase subsidy, lower electric rates or batteries purchase.

Kempton *et al.* [14] applied the approach described in [4] to evaluate the economic potential of EV for the Kanto region of Japan. The authors concluded that a decline in batteries costs, a small change in utility purchase rates, and changes in the regulation policy (e.g incentives for large-batteries) will make EV attractive to sell peak power in Japan. According to the authors if the electrical utilities perceive the additional value of EV for operating the electrical system, it would make the electric network more efficient and enlarge the market for EV.

Kempton *et al.* [15] computed the economic potential of having EV of different types (battery, fuel cell and hybrid) selling peak power in three years of the California's electricity market and the cost to the EV owner for providing the power. According to the authors, EV power capacity is limiting factor for peak power. They computed the cost of providing power to grid and found that: in battery EV the cost of battery degradation was more important than the cost of recharge electricity; in fuel cell EV the cost of hydrogen fuel and the capital cost for additions V2G interface devices are the main factors; in hybrid EV the V2G cost depends on the fuel cost and investment in V2G equipment.

The cost of electricity injected into the electrical network was estimated and found too high to be competitive for base load power, e.g. the Honda EV plus has a cost of $0.446/kWh while the baseload power price is around $0.1/kWh. The studies from Kempton *et al.* [4] and Kempton *et al.* [14] also support this conclusion.

The authors evaluated the value of V2G power for providing peak power in the day-ahead California market. The authors assumed that peak power is only sold by an EV aggregator when the forecast of the mark spot price exceeds the V2G cost. This method translates better the reality in comparison to the one described in Kempton *et al.* [14] (retail time-of-use rates) and Kempton *et al.* [4] (avoided costs). The results show that three battery EV could sell peak power with a positive net profit with the lead-acid vehicle achieving the highest profit. The fuel cell EV shows the highest potential profit for selling peak power, but the costs should be decreased in order to increase the net income. The hybrid EV if operating in the motor generator mode while parked can achieve interesting revenue and positive net income, but in battery mode is not economically attractive. In general, the results show that the peak power market when compared to the ancillary services market is the least promising since the peak power price was never high enough.

Similar conclusions were obtained by Kempton *et al.* [1], where the authors presented formulas to compute the power capacity and V2G value of the three EV types. The fuel cell EV has the ability to provide the highest power for peak hours, while the hybrid EV with small batteries does not have a significant power since are limited by storage capacity. A fuel cell EV providing peak power has a net income of $290, but as mentioned by the authors this result is very dependent on the hydrogen cost and the peak market price.

Williams *et al.* [16] also performed similar analyses for various EV types at a variety of levels of infrastructure investment. The cost per unit energy for the fuel cell EV was found to be around $0.25 /kWh. For the hybrid EV it was $0.29/kWh because of the higher degradation costs due to relatively deep discharging; according to the authors this number is very optimistic, and can be increased to $0.42/kWh if a shorter battery life is assumed. The results presented the battery EV as the less expensive in electrical energy production, with $0.23/kWh because of the lower shallow discharges and overall higher vehicle efficiency. The authors concluded that using batteries to provide peak power is of limited interest from a net income perspective. For instance, the net income of edrive Prius and RAV4EV in the peak power market are -$44 and $8 respectively. However, the fuel cell EV seems to be only type that can compete in the peak power market, e.g. the Honda FCX-V obtained a net income around $550.

Peterson *et al.* [17] analyzed the battery degradation of a Li-ion battery cell already implemented in the plug-in hybrid EV Hymotion battery pack, the A123 systems ANR26650M1 cell. The main objective was to study the response of multiple sets of these cells to estimate their behavior in both simulated driving and combined driving/V2G mode. The results were intended to inform the economic analysis of a paper published by the same authors [18]. The statistical analysis performed by the authors shows that using the EV battery in V2G mode incurs approximately half the capacity loss per unit energy processed in contrast with that related with more rapid cycling meted while driving. An important result was that several thousand driving/V2G days incur substantially less than 10% capacity loss regardless of the amount of V2G support used.

Peterson *et al.* [18] analyzed the net income that an EV owner gets from discharging the battery at high prices during peak hours for using at home, and charge the batteries during lower price hours. In this work the net income is the avoided grid energy purchases from using the electrical energy stored in the battery less the cost of electricity for charging the battery and the degradation costs related with the battery lifetime. The authors analyzed two different methods to estimate the portion of battery capacity that maximizes the consumer net income.

The first method assumes perfect forecasts for the real time prices and picks the most expensive hours for home electricity use and the cheapest hours for battery recharge. This method gives an upper bound to profit. The second method uses the prices from the two previous weeks to forecast the recharging prices of the next day (average price of 14 days in each hour). Then, the model combines the forecast for the recharging cost with the knowledge of the current real time price to decide if using the energy is profitable or not in that hour. This method gives a reasonable lower bound for the profit and a lower income in comparison with the first method.

These two methods were tested for historical price series in Boston, Rochester and Philadelphia, and for a vehicle with a 16 kW battery. The results suggest that the incentives are not sufficient to motive this kind of practices from an EV owner. The maximum annual profit with perfect forecasts and without battery degradation is between $142-249 in the three cities; with degradation included the profit decreases to $12-118, and the case with imperfect forecasts is $6-72. Moreover, if the difference between the maximum and minimum price decreases due to a high penetration of EV, then the profit would decrease.

Finally, the authors suggest that the net social welfare provided by this solution should promote incentives, in particular the ones related with avoiding the construction of new conventional plants to meet peak load.

Wang [19] analyzed the potential impact of plug-in hybrid vehicle in locational marginal prices (LMP). The results for a PJM five-bus example (with empirical data) show that as load increase varies from 0% to 10% due to EV recharging, both mean and standard deviation of LMP would increase substantially (more than 26% and 62%, respectively), therefore it would be much more expensive to recharge EV than it currently is. The authors opinion is that charging during off-peak hours to sell during peak hours could not be not very economic attractive. The analysis also shows that the spatial differences of LMP create an opportunity for battery stations to reduce their cost by choosing low LMP locations. Of course this opportunity is constrained by the price difference, distance and cost of shipping batteries. The results show that the battery stations could take advantage of the LMP distribution, and this will slow the increase rate of LMP and decrease its variance. For instance, if the electricity load increases 10% due to charging, it would only cost the battery stations 73% of what it would cost for EV drivers to recharge at home.

Turton *et al.* [20] examined EV technologies (in particular the V2G concept) in a long-term, dynamic, "bottom-up" and global energy system. The long-term impact of V2G concept on the global energy market was studied using the "bottom-up" optimization model Energy Research and Investment Strategies (ERIS) that includes a detailed representation of technologies and technology dynamics. The advantages of the V2G concept for supplying specific electricity markets (peak power, spinning and regulation reserve) were evaluated in two scenarios, one a simple baseline scenario ignoring external costs, another where a global climate policy is included.

In the baseline scenario the peak power capacity seems to be potentially more attractive, e.g. by the end of the century 3 billion of EV worldwide provide 25% of peak power demand. The authors mentioned that the EV avoid the need to build new conventional power plants and also creates conditions for accepting renewable energy.

In the second scenario, the EV still contributes to peak power capacity but there is also non-peak generation from fuel cell EV (19% of total power capacity). The fuel cell EV becomes competitive for non-peak load and even for base load power capacity; the reasons pointed by the authors are the high efficiency of fuel cells and their ability to use low-emissions fuels.

2.2 Ancillary Services

Ancillary services are functions separated from the electrical energy production market, which are used to support reliability and power quality of the power system. The functions can be provided by both loads and generators and different services can be provided, such as reactive power and voltage control, loss compensation, regulation reserve, load following, spinning reserve, non-spinning reserve. These services can be mandatory or remunerated (e.g. market sessions where the loads and generators offer bids for these services).

Kempton *et al.* [15] computed the economic value of EV for three years of the California's spinning reserve and regulation markets. The spinning reserve is provided by additional generating capacity that is synchronized to the grid. Spinning reserves must respond immediately and must reach full capacity within 10 minutes when requested by system operator.

Regulation reserve is provided by units (loads or generators) that are under direct real-time control of the system operator for increasing or decreasing generation/consumption. Regulation is used to fine-tune the frequency of the grid (maintaining at nominal value, e.g. 50 or 60 Hz, correct for the Area Control Error – ACE) by matching generation with load. This service can be divided in "upward" for the ability to increase power generation (or decrease consumption) from an operating point, and in "downward" for the ability to decrease power generation (or increase consumption) from an operating point.

In these two services the EV is paid for having available and synchronized capacity (e.g. \$/MW) and receives additional payments for energy delivered to the network (\$/MWh). According to the authors, for regulation reserve the limiting factor is the capacity of the connection lines. Despite being contracted on an hourly basis, the EV is only dispatched in periods between 4 seconds and 1 minute. Moreover, neither upward nor downward reserve is dispatched for a long period of time, only a few minutes at the time. Therefore, the battery will only charge and discharge slightly and alternating and the battery charge will only oscillate around the initial charge state. For spinning reserve, the limiting factor is the EV power capacity (or storage capability). This reserve type is called only a few times per year (e.g. 20-50) and the duration time could range between 10 minutes and 1 hour. Hence, the ability of an EV to provide this service for several minutes continuously is limited by the battery storage capacity. Of course, regarding the availability payment, the capacity of the connection lines is an important limitation factor.

For the spinning reserve market most of the EV analyzed by the authors could deliver this service with a positive net income. The battery EV can provide at an average net income from tens of dollars to \$700, for the fuel cell EV it ranges between tens of dollars to \$2000 and insensitive to fuel prices, while the hybrid EV in motor-generation can provide at a net income around $2000.

For the regulation reserve fuel cell and hybrid vehicles only provides upward regulation, assuming that it is more profitable to operate at maximum power capacity. The results show that battery EV are particular promising for this service, with a net income between $8442 and $3162 for the lead-acid battery. This is because the EV would be injecting and absorbing power under real-time commands from the system operator and over an extended period of time the net total energy balances becomes approximately zero [21]. Therefore, battery EV could perform regulation function indefinitely with a much lower deep of discharge, the battery charge fluctuates around its initial charge state. This avoids capacity issues related to battery state-of-charge, promotes less battery degradation and decreases the costs due to battery degradation. However, the degradation and replacement costs of the battery still are the most important share in the service cost.

The fuel cell and hybrid EV could not provide a positive net income in all the three years analyzed. Only in one year a positive income was obtained; one average the fuel cell EV with on-board hydrogen achieves a net income ranging from -$2984 to $811 while for the hybrid EV is -$759. The most important conclusion from this work is that some EV types are more suited than others for different markets.

Kempton *et al.* [1] evaluated the expected revenues and costs from the participation in the ancillary services market. The conclusions from the authors were consistent with the previous ones. The EV probably can only compete with centralized generators in spinning and regulation reserve, mainly because of the payment for available capacity for reserve. The authors stressed that this capacity payment could also offset the losses of selling electrical energy.

The fuel cell vehicles can provide more power for spinning reserves and peak, while the battery and hybrid vehicles can provide more regulation because both provide up and downward regulation. As an example, the battery EV have available 21 kW for up and down regulation; this means 41 kW of regulation capacity to be remunerated; on other hand, the fuel cell EV is only remunerated by 25.7 kW of upward regulation. The fuel cell EV for spinning reserve is economically viable only with a combination of “good” market prices with reasonable capital costs (e.g. wiring, on-board connections).

The economic benefits from the participation of EV in ancillary services were also studied by Kempton *et al.* [22] for a single battery EV operating under real-time dispatched by PJM (regional transmission organization). The results show that the potential value (discounted present value of gross revenues) per EV in much greater when selling regulation in contrast with selling spinning reserve. For example, with a 10 kW of power capacity the ten-year present value of gross revenues (only from capacity payments) is around $20000 for regulation reserve and around $5000 for spinning reserve.

The authors tested the EV as potential energy storage for regulation with V2G capability. The results show that power provided by the EV tracks the regulation signal very closely, and in contrast to conventional generation units, the energy is stored and injected during the provision of regulation service. The authors also stressed that it could happen that regulation provision may lead to a fully charge or discharge battery. One solution proposed by the author to overcome this problem is an aggregation agent that dispatch vehicles to match the regulation needs, e.g. a vehicle with full charge will be committed to provide only upward regulation. Moreover, the authors also propose a solution where each EV operates at a preferred operating point (POP) from what provides upward and downward regulation, similar to the operating point of conventional generators for spinning reserve.

This idea of a POP for EV is shared by Brooks *et al.* [7]. The difference between the POP of the conventional units and the EV is that the conventional units have a positive POP (e.g. dispatched generation level), while for the EV it could be zero or negative. The capacity of the regulation services is only linked to the deviation capacity from the POP. The authors presented the example of an EV with bidirectional charge providing upward and downward regulation at zero POP, and an EV with unidirectional charge providing both regulation services at -7 kW POP. For the unidirectional charge EV this means that it provides 7 kW of upward regulation until it reaches the “zero load” situation, and provides downward regulation acting as a 14 kW load. The authors’ opinion is that EV have the ability to create value by providing the downward regulation service (grid-controllable load), with several advantages over the initial V2G (bidirectional charging): it does not require additional capital costs with V2G equipment; reduces the costs with battery wear; lower losses in the charger.

The authors stated that a pilot project of EV with unidirectional charge capability is on-going, but do not present any result from this project.

Williams *et al.* [16] also evaluated the net income obtained by different EV when providing regulation and spinning reserve. The conclusions are consistent with other authors. Moreover, the authors stated that regulation and spinning reserve revenues are very dependent from the capacity price, and in a lesser importance, to the energy price offered for the reserve.

Turton *et al.* [20] evaluated for two scenarios (baseline and other with global climate policy) the long-term impact of the V2G concept on spinning and regulation reserve markets. The study shows that conventional generation capacity for both ancillary services markets is enough to meet the modeled requirements. Consequently, it is foreseen that the EV will only represent a very small portion in this type of markets. Nevertheless, Kempton *et al.* in [2] and [6] foreseen that 3% of the EV in the fleet are enough to serve the reserve needs. However, and as mentioned by Hawkins [23], the following characteristics of EV make them more attractive than conventional generation sources for reserve services: fast response, distributed location, reduces wear and tear on generators, and possibility of automatic regulation response.

Finally, note that due to historical and technical reasons the ancillary services nomenclature and time frames for load-frequency control have significant differences of implementation in various countries, as showed by Rebours *et al.* [24] in a survey paper. It is important to stress that the basic principles of each type of load-frequency control are the same. For instance, regulation reserve normally in some countries is the secondary control reserve, and sometimes also comprises primary control reserve.

2.3 Storage and Renewable Energy

Bludszuweit [25] developed a cost model for storage devices (e.g. pumping storage, flywheels) which accounts for specific properties of different technologies. A reference case was considered for forecast error compensation of a wind farm, and the major conclusion was that energy storage is roughly always considerably more expensive than the mean electricity price (in this case was 50 EUR/MWh). The results showed that only pumped hydro storage provides energy at a cost below 100 EUR/MWh. The author concluded that, from an economic perspective, investing in storage devices dedicated to renewable energy (in particular wind power) is not attractive. However, and as mentioned by Kempton *et al.* [6], if there is storage capacity already in the system we should use this capacity.

Kempton *et al.* [2] presented storage and backup power of EV as an additional service and important to accommodate high penetration of renewable energy and forecast errors. For instance, the electrical energy generated during solar peak hour can be stored and then injected into the grid during load peak hours. The backup power can be provided by fuel cell and hybrid running motor generator EV, storage can be provided by batteries vehicles or plug-in hybrids.

The main conclusions from the authors is that storage from battery and hybrid in battery mode is more adequate for the most frequent and low electrical energy shortfalls of wind energy, while the backup from fuel cell or hybrid in motor-generator mode is more adequate for less frequent and high shortfall of wind energy.

It foreseen by the authors a saturation in the ancillary services market (3% of the vehicles in the fleet are enough to serve the reserve needs), so the peak power and "storage market" are the next step according to the authors. According to Kempton *et al.* [2][6] the EV will serve the majority of need for integrating wind into the power system; EV with V2G capability can provide storage to level out the variations of wind power, even when the wind becomes half or more of the total electrical generation.

Birnie [26] presents the situation where daytime charging of plug-in hybrid EV is performed in large parking lots (e.g. at workplace) where vehicles parked all day long, named solar-to-vehicle (S2V). The author analysis shows that solar photovoltaic arrays of a size similar to one's parking space could generate enough power to carry a EV vehicle to and from work using an adequate battery size. Moreover, a parking lot of 15 m^2 area could have an average daily summertime solar generating capacity around

12.6 kWh.

Markel *et al.* [27] discussed several charging schemes based on grid communication of real time load, price and renewable generation. From the several control algorithms described the following can be used to cope EV with renewable generation: renewable energy signal, where EV are charged exclusively with renewable energy and at a fast rate when there is a high penetration of renewable energy and at a slow rate in periods with lower penetration. Different grid communication technologies were also described and analyzed. The authors simulated the interaction between EV and the electrical network using several real data sets to simulate different driving behavior, vehicle systems and electrical network. The results show that the renewable charging scheme maintains the peak load at its original level. This charging scheme also do not presents the higher battery wear costs, in contrast to schemes that are price and load responsive. The renewable resources were found to be more than enough to supply the EV fleet demands. An important conclusion of the authors was that EV can reduce the utility 10 minutes ramp rates by 5%, which means that smart charging controls in EV can help reducing renewable energy ramps.

Kiviluoma *et al.* [28] describe a model that optimizes long-term investments for switching from conventional generation to wind power by combining heat storages, wind power and EV. The authors concluded that dedicated electricity storage is not economically viable to accommodate wind power forecast errors, and the flexibility introduced by heat storage and EV could be more economical. In the scenarios and assumptions of the authors the increase in wind power was much larger with the heat storage measures than with plug-in EV; heat storage measures offered a larger flexibility while the EV are more limited. The introduction of both approaches can induce cost-effective emissions reduction in electrical energy conversion.

Lunda *et al.* [29] modeled two national energy systems (including the V2G concept) for Denmark, one with combined heat and power (CHP) and the other, similarly sized without CHP. For the case with CHP the combination of heat/cold storage and V2G was considered. The results show that EV with at least night charging (even more if they have V2G) will improve the efficiency of national energy systems by reducing surplus of electrical energy from wind power and also the national CO2 emissions. The authors also mention the possibility of combining EV with measures such as active management of CHP plants and heat pumps.

Finally, note that Kempton *et al.* in [2] see the backup and storage capability as a new service that does not exist in electricity markets, quoting the authors: "a future form of electricity provision, not now formalized into separate markets, is storage and backup power for renewable energy…". However, the current market rules in most countries already have the possibility of having storage playing an important role as a market agent. Two approaches and possible use of EV can be adopted: i) combine a fleet of EV with renewable energy facilities; for example, Costa *et al.* [30] presented a virtual power plant in which a wind farm is jointly operated with electrical energy storage facilities to take advantage of existing market opportunities for increasing operational profits while decreasing the wind power forecast error; ii) sell in the market backup power as upward operational reserve and storage as downward operational reserve, where the function of this operational reserve is to deal with forecast errors of generation (e.g. wind power) and load, and with unit outages.

2.4 Other Possible EV Services

According to Brooks *et al.* [21] there are possible additional services for EV like reactive power management, peak shaving and backup power.

Cage [31] reported tests of a prototype hybrid plug-in electric vehicle (a modified Volkswagen Jetta) with an 8 kWh battery combined with an onboard generation source. According to the author the EV can provide services to benefit the local operation of the network where is plugged as an on-site generator. For instance, the EV can act as a UPS (uninterruptible power supply) to support the power needs of a house. Other possible local services consist in: local voltage control for power quality improvement, loss reduction at the low voltage level, and peak shaving. These distribution network support services were also mentioned by Kempton *et al.* [22].

Lopes *et al.* [9] determined how voltage profiles, losses and congestion behave when subject to different penetration levels of EV. The results show that peak shaving with smart charging (charging distributed along the valley hours) allowed an EV penetration of 52%. Lopes *et al.* [32] extended the previous work to analyzing the impacts of peak shaving with smart charging for prevention of wasting renewable energy. The authors also mentioned that this smart charging strategy can prevent congestion and provide voltage control. Therefore, the peak shaving service is technically attractive when combined with smart charging.

Fell *et al.* [33] analyzed the possible services that an EV can provide in the U.S. markets acting only as a controllable load. Peak power, regulation, spinning and non-spinning reserves were also mentioned by these authors. In addition to these services, the EV can provide quick response load-curtailment resource in emergency events, which could serve in a reliability-based or economic demand response capacity. The authors also described the dynamic pricing scheme. In this scheme the EV would automatically determine whether or not to charge, given the real-time hourly price, in response to an intelligent application installed on-board or to a signal from an aggregator or charging station. According to the authors this might be a way to accomplish the charging of EV batteries in off-peak hours.

Lopes *et al.* [34][35] presented results about the provision of primary frequency control by EV acting as a controllable load and/or storage device. However, this type of service normally is mandatory and is not subject to remuneration. The opinion of the authors is that EV may be the solution for the frequency problems verified in microgrids, in particular during islanded operation.

3 AGGREGATION AGENT OF EV

3.1 Concept and Role

Section 2 presented the possible services that EV can provide, from an economic and technical perspective. However, despite some services like demand response could be provided by individual EV, these services can only have a significant impact on the electrical network and sold in the electricity market if provided by a large fleet of EV.

For instance, Fell *et al.* [33] in the study performed for the ISO/RTO Council (IRC) in U.S. recognized that: "an aggregator will coordinate the application of multiple EV to meet product or service commitments to the ISO/RTO while also achieving targeted charge levels per commitments to the vehicles (…) an aggregator will need to sign up a sufficient number of EV to provide the product or service and meet the requirements specified by the ISO/RTO to participate in the market". Moreover, Kempton *et al.* [1] mentioned that the main limitation for participating with peak power is the requirement to supply power between 3-5 hours, which for a single EV (in particular battery and hybrid) would be impossible due to storage limitations.

For this purpose, in 2001 the concept of an actor that aggregates EV was introduced in the literature by Kempton *et al.* [15]. The authors assume that each vehicle owner cannot bid in the electricity market nor have transactions with electrical utilities due to a lower power capacity (kW rather than MW). The solution is an aggregator that serves as a middleman between vehicle owner and electrical utilities or electricity market. The aim of the aggregator is to represent a large power capacity (at least 1 MW) that can be sold in the electricity market or by a contract established with an electrical utility.

Brooks *et al.* [21] also introduced the concept of a middleman company that aggregates a large number of EV and provides a single contact point with a system operator. The interaction between the aggregator and the EV owners shall be performed considering the fundamental principle that the highest priority of an EV is transport. Therefore, the authors proposed an operation where the drivers communicate their driving needs to the aggregator, and the aggregator manages all this information. With all the driving profiles the aggregator creates a "virtual power plant" where the number of vehicles expected to be plugged at any given time of the day is know, and how much electrical energy and power are expected to be available. Real time data (location, state of charge, power capacity of interconnected EV) would be used to update the expected availability. According to the authors, the main advantage of an aggregator is that the total power and available electrical energy in each hour would be forecasted with less uncertainty in contrast with a single vehicle.

The same aggregation agent is mentioned by Brooks [36] and Kempton *et al.* [1]. Kempton *et al.* [22] mentioned that EV when aggregated in a large number can provide dispersed storage for electrical energy from renewable sources.

Guille *et al.* [37] propose a conceptual and practical framework for implementing a large deployment of EV. The core of this framework is an aggregator that provides interface between the system operator and the electricity energy provider (e.g. Distribution Company, electricity retailer). In this framework the aggregator is a central actor and decision maker that deals directly with the system operator for supplying energy and capacity services (on the supply-side), and with the local electricity energy provider for charging the batteries (on the demand side). Moreover, it could have economic benefits when purchasing electricity, batteries and other services, mainly because it is a large purchaser.

The communications requirements of such framework are also described by the authors. For instance, the aggregator must monitor the status of each EV (e.g. state of charge), collect the data for the services provided to the system operator and EV owners, control the services provided by the EV, receive signals from the system operators and EV owners, and metering the power flows.

Lopes *et al.* [34] described an architecture where EV are embeded under the MicroGrid (MG) and MultiMicroGrid (MMG) concepts, with a hierarchical control scheme. This paradigm, in what regards EV, has the following components: vehicle controller (VC) of the charging/discharging process of batteries; clusters of vehicle controllers (CVC) which represent EV fleet charging and charging stations; Central Autonomous Management controller (CAMC) installed at a MV/HV substation level and responsible for managing a large amount of EV plugged with the grid; MG Central Controller (MGCC) acting as an aggregation agent connecting the CAMC and the vehicle controller in the MG (also control loads and microgeneration). The MGCC sends set-points to the corresponding vehicle controller, related with charging rates, adjustment of operation droops (for primary control) or request the provision of AGC.

Lopes *et al.* [35] and Almeida *et al.* [38] rethought this framework to include the electricity market and also an aggregator differing from the MGCC established in the previous framework. In [35] the aggregator acts as an intermediary between the EV owners and the electricity market, by acquiring electrical energy in the market and offering several services in the market. In this framework the aggregator could be responsible for providing secondary control (dispatched via Automatic Generation Control - AGC) to simplify the communication process between the AGC and thousands of EV. The aggregator will receive set-points from the transmission system operator (TSO) according to its participation factor and will distribute it among the EV fleet. Moreover, it can also interact with the distribution system operator (DSO). For instance, the DSO communicates to the aggregator how it wants the EV to behave when frequency deviations occur; after receiving this information, the aggregator will send set-points to each EV in order to adjust their droops to provide primary control. The aggregator can also interact with the DSO in order to solve congestions in the distributional network.

The framework proposed by Almeida *et al.* [38] to cope with EV and microgrids is slightly different from Lopes *et al.* [34]. In this work, the aggregator is composed by two types of sub-entities with hierarchical dependence: Central Aggregation Unit (CAU) and the MicroGrid Aggregation Unit (MGAU). The CAU is physically connected to the MV/HV substations, and the MGAU links the EV (through a vehicle controller) and the CAU. An aggregator may have several CAU and each CAU will communicate with several MGAU.

For Quinn *et al.* [8] the aggregator is seen as a command and contracting architecture that aggregates EV to make a single controllable source of regulating reserve. The aggregator receives request signals from the system operator and transmits commands to the EV that are available and willing to sell the service. In this architecture, the aggregator can bid into in the hourly ancillary services market at any time, and the EV can engage or disengage from the aggregator as they leave or enter the charging station.

The concept of an aggregator for Galus *et al.* [39][40] is different; their opinion is that the aggregator is not a company. Instead, it is an abstract computational entity monitoring the control area. It acts as an intelligent interface between the EV and the energy hub agent, and exchanges information between both.

The main functions of this aggregator are: adds arrived EV and removes departed EV from a list; updates the EV list; dispatches optimally the available energy in the EV fleet; communicates the available energy to the energy hub agent.

3.2 Economic and Technical Issues

Brooks [36] evaluated the feasibility and practicality of having EV providing the regulation reserve service (dispatched viaAGC). The test was performed in a Volkswagen Beetle converted to electric propulsion with an 18 kWh battery (Panasonic lead-acid model) with bidirectional interface with the electrical network and dispatched remotely by wireless communication.

The use of wireless internet communications creates the opportunity to manage the power flow of compounds of EV by remote control. An aggregator function was developed to serve as the middleman between the system operator and multiple vehicles.

The economic value from this service beats the battery wear cost (only this cost was considered) under almost all operating conditions; the cost of battery is between 20% and 60% of the annual gross value created. Moreover, the battery capacity increased by about 13% during the test, but according to the authors the only consistent conclusion is that no harm was done to the battery pack during the test.

Almeida *et al.* [38] presented a methodology to make EV aggregators able to participate in AGC control. Some modifications were introduced by the authors in the traditional AGC in order to make possible the EV response to changes in system frequency and schedule power flows in interconnection lines. The studies were conducted for an equivalent of the Portuguese transmission and generation system, including interconnections with Spain. The scenario considers 1.5 million EV (20% hybrid with 1.5 kW, 40% with 3 kW, and 40% with 6 kW), corresponding to 30% of the entire Portuguese light vehicles fleet. The EV were modeled as an aggregated controllable load that provides secondary reserve by reducing its load until reaching zero consumption; the V2G mode was not tested in this work.

The results show that the AGC response with EV participation is faster than with EV as non-controllable loads. Without EV the total reserve levels considered in the study would be insufficient to recover the schedule interconnection value, while this is possible with the additional reserve provided by the EV. Moreover, when EV participate in AGC there is a faster reduction in the value of line loading after the disturbance, and the area control error assumes values near zero after 10 minutes. The final conclusions were that EV aggregators participating in AGC improve the system dynamic behavior and the simplification of the communication infrastructure allows a fast communication of set-points.

Tomic *et al.* [41] analyzed the net revenue of two real fleets (100 Th!nk City and 252 Toyota RAV4) with battery EV that provide regulation reserve in four US electricity markets. Regulation up and down of the first fleet was found to be profitable in all years (with exception of 2001) of New York ISO market, but the authors found that it was more lucrative to this fleet to provide only regulation down (the EV operates just as a grid-controllable load). For the second fleet, the regulation up and down was found to be very lucrative in the New York ISO.

The analysis was extended to three additional electricity markets in US. The results show that the first fleet could provide regulation services with profit in three markets (in the other the market value of ancillary services is lower), and the second fleet presents high profits in most of the markets. These results support that the economics of fleets are very attractive.

Quinn *et al.* [8] compared the situation with a direct communication between the system operator and EV owner (also named deterministic), and the situation with an intermediate communication between the system operator and an aggregator. According to the authors an EV providing regulation reserve should satisfy two important requirements for a system operator: availability and reliability. The availability factor of EV for V2G services was quantified and compared for the two possible architectures. The results show that the direct architecture is less available during large portions of the day, while the aggregator availability is almost 100% and so reserve services can be contracted at any time.

The reliability of EV, represented by the forced derated hours ratio, was also computed and compared. The direct architecture is less reliable than the aggregator, mainly because the direct scheme relies totally in the uncontrolled behavior of EV owners. The aggregator scheme can control the reliability through the contracted fleet size, the contract size, or both. As a conclusion, the aggregator architecture from the system operator viewpoint is the best solution.

The authors, in addition to analyze the viewpoint of the system operator, consider the angle of EV owners. The robustness of the return on their investment in hardware and vehicles was compared for two architectures: one with direct communication with the system operator for selling regulating reserve, and other throughout an aggregator for providing regulating reserve.

New economic models to compute the potential revenue from selling regulating reserve were presented. The new models adopted the revenue and cost framework described in Tomic *et al.* [41] and extended it to include time varying contract price (time series of ancillary services prices), time varying availability and reliability.

The average annual revenues and costs were computed for an average V2G vehicle owner (minute-by-minute availability of an average vehicle calculated using the National Household Transportation Survey dataset) under the direct architecture. The average gross profit was $1374 per year for an average gross margin of 58%. Another conclusion from the authors was that there are days and weeks of the year where reserve services are very lucrative.

The same calculations were performed for the aggregator architecture. The aggregator splits the hourly revenue among the vehicles that were connected using the ratio of minutes that each vehicle was connected. The annual revenue and cost of a particular vehicle with driving habits equivalent to the driving habits of an average NHTS vehicle was computed for this architecture. The average gross profit is $662 per year for an average gross margin of 58%. The authors also computed the return on investment for both architectures. Both have positive net present value with profits of $7643-7943 for the direct and $3268-3568 for the aggregator.

The results show that the aggregator architecture limits the amount of initial investment that a EV owner can payback and also the gross profit (but sill with a positive net present value), and therefore from the EV owner viewpoint the direct architecture is more attractive.

However, some assumptions in the paper can explain the economic difference between the two architectures. First, the EV in the direct communication architecture is always paid for being available (capacity payment) and dispatched (energy payment); however, in some hours, the EV may not be assigned to provide the service or dispatched. Second, it is assumed that the aggregator increases the fleet size in order to guarantee a reliability standard and this limits the profit obtained by the particular EV, when compared with a single EV without this requirement.

Finally, it must be stressed also that the same authors [8] state that “only the aggregative architecture is mutually acceptable to all stakeholders and can provide a more feasible pathway for realization of a near-term V2G ancillary services system”.

The next subsection presents business models described in the literature.

3.3 Business Models

The general opinion in the literature is that the figure of an aggregator is important to the success of the V2G concept. Moreover, it is also important to define and study business models for an aggregator. For instance, a proper business model would be the answer to the problem mentioned by Brooks *et al.* [7]: “bidirectional V2G implementation will require resolution of who is responsible for potential battery wear costs”.

Kempton *et al.* [15] describe a business model where the aggregator provides free replacement batteries and possible free charging or cheap charging, in exchange for being able to use the vehicle power. The advantage of this model is that the aggregator is only entity responsible for technically managing the batteries (e.g. deep of discharge, cycling) and for the replacement. Moreover, the driver needs must still being respected and managed.

For Brooks [36] the aggregator is a commercial middleman that communicates and makes transactions directly with the grid operator and then share the value created with connected vehicles. The commercial interaction with the vehicles owners can be throughout direct payments, subsidized leases, or ownership and/or warranty of the vehicle battery pack by the aggregator.

Kempton *et al.* [15] in 2001 and four years later Kempton *et al.* [2] described different business models for the aggregator. The authors present three possible business models. The first model corresponds to having an aggregator that manages time availability of fleet use for transportation and sells services directly to the system operator or to the electricity market. In this model it is foreseen that the fleet is parked in a single location and connected to a single network point.

The second model consists in using power from dispersed vehicles but with a business partnership with an electricity retailer company. In this case the aggregator is the retailer company which buys power from hundreds or thousands of vehicles and sells this power in the electricity market. In this model, the aggregator does not have any control over the individual vehicles, but can provide financial incentives to stay plugged when possible. The payments to EV will be included in the electricity bill.

In the third model instead of an electricity retailing company the aggregator could by a company from a different business area. The aggregator could be a battery manufacture that offers free replacement batteries in exchange for some of the profit from selling energy to the grid, or cell phone network that may provide communications functions and other services similar to the ones used for cell phones, or a Energy Service Companies (ESCO), or a or a third party specialized in electricity markets or electricity retailing. .

Guille *et al.* [37] described the business model called "package deal" to attract and preserve EV owners with proper incentives. The aggregator provides preferential rates for the acquisition of batteries, maintenance and discount rates for charging and parking the EV. In exchange, the EV owner is constrained to plug the vehicle at times determined in the contract. The incentive for long term contracts is higher than short term commitments, possible incentives is a guarantee for the battery or lower tariffs for charging or parking the vehicle. If an EV owner fails to meet the contract it is penalized by losing all discounts and/or battery maintenance, or in the limit the contract is canceled. Premiums are also considered for "well behaved" EV owners.

The aggregator can use its large purchase power to negotiate better prices and conditions (e.g. extended warranty) with battery manufactures and parking lot owners, and offer these services as part of the "package deal". This model is appealing for an EV owner because it offers lower charging rates and the owner is no longer concerned about battery degradation. This will decrease the investment and operational costs of an EV.

A different business model, from the company Better Place, is analyzed by Andersen *et al.* [42]. The core business consists in a creation of an Electric Recharge Grid Operator (ERGO), which has the following basic elements: charging points grid with a smart metering infrastructure that communicates with its users and manages the charging of each vehicle; partnership with vehicle, batteries and hardware manufactures; separate battery ownership from car ownership by offering several kinds of leasing deals for batteries or even for vehicles.

The investment and operational costs of the model are the recharging points structure, the communication network and the batteries. In addition to recharging points, battery replacement stations for trips above 160 km are also considered. With this model, Better Place can be seen as an integrator and infrastructure provider, as well as intermediate (aggregator) coordinating all the information, power flows and available power capacity.

The idea is to operate the battery leasing as a cell phones communication business. The EV owner pays for the power they consume to travel kilometers, in analogy to the payment per minutes in communications. Different leasing schemes can be arranged for the batteries, e.g. paying for using the battery for a predefined number of kilometers. It should be noted that the current model does not explore the V2G concept, but it is foreseen to be canvassed and the ERGO will promote this transition.

Andersen *et al.* [42] also mentioned the partnership between the Danish electrical utility DONG Energy (owner of several wind farms) and Better Place. The model proposed by Better Place would allow EV to be a storage device for wind farms generation, making possible the creation of virtual power plants.

Williams *et al.* [16] support the idea that with an aggregation agent it is possible to increase the profitability margin of the V2G paradigm. With an aggregator each vehicle will not support individually the V2G infrastructure and communication costs. The business model presented by the authors consists in using idle airport rental cars to provide system services to the electrical network as a virtual power plant. The advantages of this model are that might smooth the rental car revenue variability while increasing the public acceptance of EV by decreasing the rental costs.

4 ALGORITHMS FOR MODELING AND SUPPORTING AN EV AGGREGATOR

The results and conclusions of Tomic *et al.* [41] regarding the participation of two battery EV fleets in the regulation market are important to understand what kind of variables affect the aggregator decisions and what are the decision variables. Quoting the authors "each market should be evaluated on its own to determine if it is economically more interesting to provide both regulation up and down or only regulation down…", therefore the aggregator needs to define ex-ante which markets are more probable to provide an higher net income, or in alternative which vehicles (or how many vehicles) should be aggregated to increase the profit in a given market. According to the authors the important variables are: the value of ancillary services in the market, the power capacity (kW) of the electrical connections and wiring, and the storage capacity of the EV. The amount of time the vehicles are on the road or discharged was not found to be a relevant variable.

Caramanis *et al.* [43] addressed the problem of management EV loads within an electricity market environment. A decision support method was developed for an EV load aggregator (an ESCO company that manages EV charging) aiming to achieve cost saving in battery charging and provision of regulation services required due to a wind farm. The method works as follows: in the beginning of each market period (day-ahead and real-time) in a 24 hour cycle, the aggregator buys electricity from the real time wholesale market and presents bids for the up and down regulation service over 5 minutes interval. It is assumed that the aggregator has access to information about congestion constraints in the local distribution network. The wind farm generation forecast and clearing prices are used together to make optimal feasible decisions regarding the quantity and bid prices for buying electrical energy and offer regulation services. Additional batteries are considered to cope with upward regulation service. A rolling horizon look-ahead stochastic dynamic programming algorithm solved by linear programming is described for hedging in the day-ahead market and for bidding in the real-time market in order to have regulation service revenues and discounts on the use-of-distribution network tariffs.

Capion [44] developed a model that defines the optimal charging plan for EV fleets by minimizing costs for a fleet operator in Western Denmark. The model is only for the day-ahead spot market. The objective of the fleet operator is to minimize total costs (fuel, electricity and battery wear), which consists in charging at a lower price while limiting liquid fuel consumption and sell power if profitable. The problem is limited by several constraints, such as the electrical energy balance of the battery, limitations of the power line and technical limitations of the battery. The drive patterns were computed with a k-means clustering algorithm.

The model is deterministic and the authors assumed perfect forecast for all the variables involved in the problem. The results show that the optimal strategy charges the EV mostly during night, where the prices are lower. However, when the penetration of EV increases, the prices during night also increase. This increase in price will decrease the incentive (difference between peak and valley prices) to store and sell electrical energy. In all the scenarios analyzed by the authors, only a little amount of electrical energy is injected into the grid. The main reasons were the small price differences and the battery wear cost. According to the authors, when the EV penetration grows the economic opportunity to sell electrical energy decreases. The possibility of selling reserve services was not considered.

Clement-Nyns *et al.* [10] formulated an optimization problem to minimize power losses and voltage deviations in the electrical distribution grid. The V2G concept was not considered by the authors. The authors presented a deterministic formulation where the objective function was minimizing power losses, subject to technical constraints of the electrical network and of EV. A stochastic approach was presented to include the forecast error of the daily load profiles, which is represented by Gaussian distributions. The difference between the power losses in deterministic and stochastic optimum was small, and the authors concluded that the load forecast error does not have a larger impact on the power losses. Another objective was to show the advantages of smart charging (while charging at home) to improve the power system quality in contrast to a situation with uncoordinated charging. The results show that power losses and voltage deviation are reduced (into levels similar to the situations without any EV) if coordinated charging is performed. Moreover, the difference between the power losses in coordinated and uncoordinated charging is more pronounced in the stochastic formulation.

The authors compared quadratic programming with dynamic programming for solving both deterministic and stochastic problems. The results showed that the difference between the two techniques is negligible, but the storage requirements of the dynamic programming are much heavier and increases the computational time.

One important aspect of this optimization problem is that the EV owners (and aggregator) have no longer the possibility of controlling the charging profile. The only parameter left to the owners is to indicate the time instant where the battery must be fully charged. Therefore, the aggregator could modify its formulation to increase the flexibility of the algorithm.

Vlachogiannis [45] presents a probabilistic constrained load flow (PCLF) suitable for power systems with wind power generation and EV demand or supply. Generally, the end-users of power flow models are system operators and distribution operators, and the aggregator does not have any particular interest in this tool. However, this is a novelty in the state-of-the-art because it couples EV and wind generation in power flow studies, and also allows the modeling of wind power and EV stochastic characteristics.

Saber *et al.* [46] describe a unit commitment (UC) considering EV. The objective function of the UC is to minimize operational and emissions costs. In addition to a large number of technical constraints related with the power system others constraints are considered, e.g. meet the forecasted load; parking lot limitations; state of charge of plugged vehicles; spinning reserve requirements.

Since the problem is a combinatorial optimization with binary variables (on and off of conventional generation) and integer variables (number of connected EV) the authors propose a balanced hybrid particle swarm optimization (PSO) algorithm. The EV are assumed to be in restricted parking lots, thus the level of detail does not go to individual EV. The algorithm determines the number of EV that can be charged every hour for a 24 hours time horizon. The results show that the algorithm improves the operational costs and emissions, and also increases the power system reliability. The next step is to apply the UC algorithm to real world applications. The potential end-user for a UC tool normally is a system operator or a generation company. However, a comparable tool could be developed and combined with a dispatch strategy to help the aggregator in its activity.

Kempton *et al.* [2] describe two possible dispatch strategies for an aggregator of EV. The authors do not present any mathematical formulation or algorithm for these strategies. In the first strategy, in addition to consider the drivers needs, the aggregator needs to dispatch each vehicle by maximizing efficiency and minimizing the wear of a vehicle. Moreover, the dispatch strategy should also be according to the EV type, e.g. for battery EV lower power levels both minimize wear and maximize efficiency, while the optimal dispatch for hybrid with motor-generator is running at maximum power.

The second strategy consists in dispatching the EV in a different way for each market, or in alternative to coordinate with a renewable energy plant. For instance, for up and down regulation the battery should be only partially charged. As an example the authors gave the following: a vehicle is parked with a partially charged battery and provides up and down regulation, then it is switched only to down regulation mode or storage to charge the battery and prepare for the next excursion.

Galus *et al.* [39][40] propose a modeling approach for EV, with an integration scheme modeled by an energy hub agent and an EV aggregator. The energy hub agent is responsible for managing the control area and has the following tasks: compute maximum possible additional load and communicate this information to the aggregator; optimally dispatch the energy carriers dependent on the EV load. The aggregator is the link between the connected EV agents and the energy hub agent that supplies the charging electricity. The authors describe a demand management scheme for the aggregator based on mechanism design theory (or reverse game theory). The aggregator tries to recharge all EV plugged in its control area while maximizing their total utility in each time step. The EV are modeled to increase their value of energy individually over time as they try to reach their individual objectives and respect the technical constraints. Reactive and proactive behavior is incorporated, and electricity prices are also incorporated in the model.

Gille [47] analyzed the nature of the uncertainty related with the impossibility of forecast perfectly the individual EV schedules (e.g. traveled distances) and the amount of energy stored in each vehicle. A model was developed, with several reasonable assumptions, to simulate the impact of aggregated EV as a load and generation source. Independent random variables (e.g. battery state-of-charge, distance travelled) corresponding to each EV and random processes were included in the model. The random variables were assumed to be Gaussian distributions. The main function of this probabilistic model is to provide a better understanding of the effect in the aggregation of the inherent variability in the behavior of the different EV. For instance, the model provides an estimate of the number of EV plugged to the grid at any instant in time and the available storage and generation to the aggregator.

The simulations performed by the authors reported important conclusions: the aggregator is important to mitigate the uncertainty related with the EV, large aggregations allow the provision of several services despite the fact that not all the EV are plugged; the size of the aggregation is a critical variable and defines the importance of the aggregator for the power system.

Finally, this methodology can be used to define the number of vehicles that are required for the fleet, and also to define availability patterns that will allow a better planning for the aggregator.

5 Conclusions

The current state-of-the-art in the topic of EV aggregation agents is further devoted to studying the integration of EV in the electrical network and power system operations. Several authors are extending the traditional power system analysis tools to include the EV as distributed flexible load and generation source. The development is based on studies performed for other distributed generation sources (e.g. combined heat and power, wind turbines) and with a strong link to the MicroGrids and MultiMicroGrids concepts. Generally, the outcome of this research is the main benefits for a power system from the massive integration of EV when new management procedures (e.g. smart charging) are used. The results show an increase stability and power quality in the electrical network, distributed generation near the loads (e.g. lower losses) and inexpensive storage for electrical energy from renewable sources.

Nevertheless, there are other research directions more interrelated with the economic and technical value of EV, and in particular with the introduction of an aggregation agent in this business area, that can be grouped in the following two research lines.

The first research line consists in analyzing which market services are more attractive for the EV and which type of EV are more suitable for each market. The most important conclusions from this survey were:

- some EV types are more suitable (in both technical and economic aspects) for some market services. Fuel cell EV shown the highest potential for selling peak power, battery EV present an higher potential for the regulation reserve market, battery and hybrid EV are also attractive for the spinning reserve market. Fuel cell and hybrid EV can only provide upward regulation reserve due to technical limitations;
- the ancillary services market is the most economically attractive but will be quickly saturated;
- the coordination of renewable generation and EV storage capability is very attractive for all involved stakeholders. In particular, the combination of renewable energy facilities with EV decrease the forecast errors of renewable generation (which increases the reliability of the power system) and represent a win-win situation in economic terms for both EV owners and renewable energy owners.

Nevertheless, the economic analyses reviewed do not include several benefits such as: reduced GHG emissions, enhanced reliability of the network, reduction in losses, voltage control and investment deferral in transmission and distribution networks.

The second line of research is devoted to the discussion of different architectures and framework for the integration of EV. In this line of research a common actor is the EV aggregation agent. The aggregation of EV was found to be technically attractive and economically valuable if a good business model is adopted. It seems that this is the better way for encourage the V2G concept and in general to favor the deployment of EV. Some of these works are also useful to perceive which decisions an aggregator must make and which decision-making algorithms should be developed.

Moreover, the introduction of an aggregation agent could change the conclusions obtained by the authors from the first line of research. For instance, an aggregator can solve the limitation of the storage capacity in battery EV and overcome the main drawback to provide peak power.

As a final conclusion, the literature in this topic is still limited and some of the concepts and ideas require a generalization to other environments, in particular for electricity markets in Europe. The concept of aggregator is already established in the literature, but needs clarification about the interrelations with different stakeholders and how the business model should be adapted for different conditions and regulations. Moreover, there is a potential for algorithms that manage the uncertainty and support rationally the aggregator decisions through decision-aid methodologies and tools.

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