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Participation of Electric Vehicle Aggregators in Wholesale Electricity Markets: Recent Works and Future Directions

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***Abstract*— Electric Vehicles are key to reducing carbon emissions while bringing a revolution to the transportation sector. With the massive increase of EVs in road networks and the growing demand for charging services, the electric power grid faces enormous system reliability and operation stability challenges. Demand and supply disparities create inconsistency in the smooth delivery of electrical power. As a potential solution, EVs and their charging infrastructure can be aggregated to prevent the unwanted effects on power systems and also facilitate ancillary services to the power grid. When not need for transportation purposes, EVs can leverage their batteries for power grid services by participating in the electricity market via mechanisms coordinated by system operators. Hence, the market participation of EV infrastructure can help alleviate the power grid stress during peak periods. However, further research is needed to demonstrate the multiple benefits to both EV owners and power grid operators. This paper briefly overviews the existing literature on market participation of EV aggregators, discuss associated challenges and needs, and propose research directions for future research.**

Keywords*— Aggregators, ancillary services, electric vehicle (EV), wholesale electricity market.

I. Introduction

Greenhouse gases (GHGs) are key contributors to environmental pollution and the global warming. In 2019, the transportation sector accounted for 29% of the emitted GHGs in the United States (U.S.) [1]. To help mitigate the problems associated with GHGs, policymakers in many countries and regions have started to endorse the shift towards increased transportation electrification. High penetration of electric vehicles (EVs), together with higher production of clean and renewable energy (RE), have the potential to mitigate environmental issues and fossil fuel depletion and enhance the energy usage efficiency in the transportation sector [2, 3]. By 2025, the total number of passenger EVs globally is projected to reach 14 million, according to according to BloombergNEF's EV Outlook [4].

Notwithstanding the promising electrification outlook of the transportation sector, some factors are hindering the adoption of EVs worldwide. The list includes the insufficient number of EV charging stations (EVCSs), the need for additional investment in electric grid infrastructure, EV motion range anxiety, and the possible overburdening of existing power systems with the simultaneous uncontrolled charging of numerous EVs during peak hours. One of the main technical concerns is that the significant penetration of EVs and charging infrastructure can eventually overwhelm the existing power grid [5]. Therefore, controlling the interactions of EVs with the power system and transportation system synergies can anticipate the upward trend of EV adoption and provide more opportunities to harness electrified transportation and power grid synergies in the upcoming years [6].

Electricity market mechanisms can also help alleviate the power grid overload caused by a large number of EVs. Time-of-use (ToU), as a preliminary form of demand response strategy, is one solution to lessen the uncertainty amount of uncoordinated charging. However, due to the necessity of using transportation system and the need to keep it dynamic, additional and more influential coordinating factors are needed to prevent any detrimental effects on the power system. In this respect, EVs can be charged under centralized or decentralized control schemes and provide grid services in an aggregated way. The aggregation structure can also facilitate the EV participation in wholesale power markets through which the whole amount of electricity cost of EVs charging will be reduced.

Based on the storage capability of batteries in EVs and the mobility characteristics of EVs, the aggregated amount of EVs can be regarded as distributed energy resources (DERs). An instance, the US Federal Energy Regulatory Commission (FERC) issued Order NO. 2222/2020, enabling DERs with more than 100kW capacity to directly participate in wholesale electricity markets through energy and ancillary services [7]. Through this manner, EV aggregators can provide and be compensated for energy and important ancillary services that include voltage and frequency regulation and supplemental reserve, to the power grid [8, 9].

This paper briefly overviews the existing literature on power market participation of aggregated EVs and the EV infrastructure. It also discusses related challenges and proposes future research directions. To the best of the authors' knowledge, this paper is the first work to review the existing literature on this topic and discuss the associated challenges and research needs. The remainder of this paper is divided into three sections as follows. Section II overviews the current literature by dividing the EV aggregators' participation in wholesale electricity markets into two categories: wholesale energy markets and ancillary services markets. This paper also classifies the related research papers into another category, consisting of unidirectional and bidirectional power flow working structures considered for EVCS and EV aggregators. Section III discusses related challenges, needs, and directions for future research. Section IV provides relevant conclusions.

II. Electricity Market Participation of EVs – Current Literature

Recently, the EV participation in electricity markets has garnered extensive prominence from researchers around the world. Although EVs are now considered an integral part of the electrical system, a single EV or an EVCS cannot effectively participate in wholesale electricity markets due to its low storage capacity. However, multiple EVs can be properly aggregated into a single resource to participate in electricity markets and provide important services to the power grid. Fig. 1 illustrates the main interactions between an EV aggregator and multiple agents in power and transportation networks.

Power systems are generally operated in conjunction with well-structured electricity markets. Wholesale electricity markets usually comprise large power generators and consumers that participate in competitive and sequential trading platforms, such as day-ahead and real-time (or balancing) markets [10]. Furthermore, ancillary service markets, considered a vital part of the wholesale market, ensure the resilience and reliability of electrical transmission systems [11]. The structure of the wholesale market and in respect to the interactions with an EV aggregator is illustrated in Fig. 2. Retail electricity markets, on the other hand, handle smaller energy transactions between smaller-scale customers at the distribution grid, electricity retailers, electric utilities, etc. This paper focuses on the participation of EV aggregators in different types of wholesale electricity markets. To this end and to compare the literature more effectively, the research works are divided into two parts: the wholesale energy market and ancillary service markets.

Furthermore, whether EVs work in the discharging manner with a view to participating in providing power system services or not [12], two scenarios of bidirectional and unidirectional operational viewpoint were also considered for each EV aggregator in interacting with the power markets. It is worth mentioning that even if an EV aggregator is considered to work in unidirectional manner, it is still capable of providing technical services to the electric power grid by changing the amount of power to charge the EVs. Table I shows a comparison chart of different works and modeling techniques utilized for EV participation in electricity markets.

A. *Participation of EVs in Wholesale Energy Markets*

In the US, wholesale energy markets are mainly comprised of day-ahead and real-time markets. In the day-ahead market, system operators schedule electricity generation and consumption along with the commitments of ancillary services

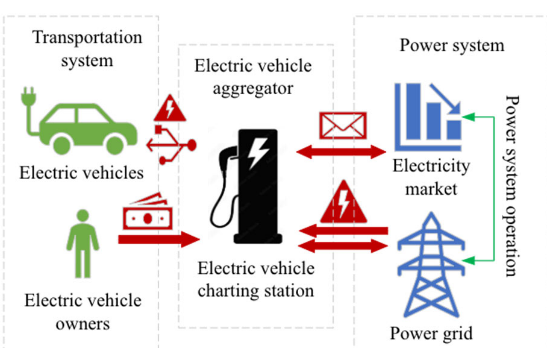

Fig. 1. EV charging station interactions.

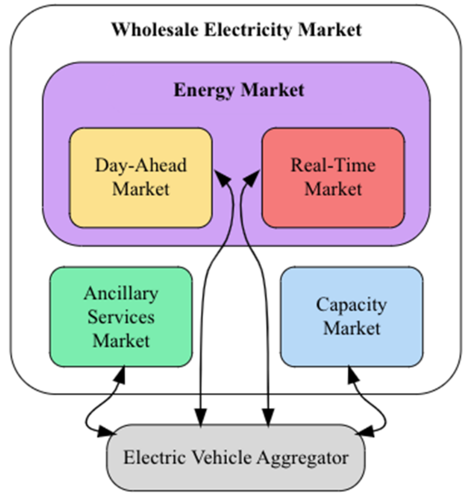

Fig. 2. EV aggregator possible interactions with wholesale electricity markets.

one day ahead of the operation day. Conversely, the real-time market is designed to amend imbalances between the day-ahead schedules and real-time load or generation throughout the operation day.

1) *Day-Ahead Energy Markets*

Several papers proposed methods for the optimal power offering or bidding of EV aggregators in wholesale day-ahead electricity markets. Some of these papers concentrated on the charging/discharging management of aggregated EVs in energy markets only. Ref. [13] discusses the load scheduling operation problem and proposes its modeling in the way that offers of buying energy from the wholesale power market from the aggregator side are dedicated for the nighttime off-peak hours, when most EVs are not being used and the electricity prices are low. The work in [14] proposed a model in which the EV charging schedule relied on EV owners' choices and preferences. The energy offer by the aggregator is dependent on the energy price and the energy requirement of EVs. The latter one is variable because EV batteries are not always charged to full capacity. This flexible approach can encourage the participation of more EV owners in electricity markets based on pricing.

Some other papers sought to design a working structure for EV aggregators in which the EVs are supposed to be more like flexible loads in a way that not only their charging scheduling problem can be shifted to the time or structure that cost less, but also to earn additional revenue. Although the EVs are still operated in the unidirectional power flow structure, meaning that the aggregated EVs just demand power from the grid without injecting it to the grid, they can facilitate demand response programs (DRPs) and provide some services in day-ahead energy markets. An optimal participation of aggregated flexible load including EVs in DRPs was proposed in [15]. The aim of this study was to provide energy services in the related markets through unidirectional manner. The constraints related to the operation of EVs, the uncertainties regarding the price, and battery aging were taken into account. A robust optimization framework through a receding horizon type of linear approach was proposed in that reference to find the best operational framework for the flexible aggregated load. The work in [16], in a similar way, described the EV participation

TABLE I. COMPARISON OF DIFFERENT OPTIMIZATION METHODS FOR EV MARKET PARTICIPATION.

Optimization Modeling / Market Participation	**Energy Market**				**Energy & Ancillary Services Markets**	
	Day-Ahead Only		**Day-Ahead & Real-Time**			
	Unidirectional	**Bidirectional**	**Unidirectional**	**Bidirectional**	**Unidirectional**	**Bidirectional**
Linear Programming				[22]		[28], [31], [33]
Mixed Integer Linear Programming		[19]	[23]			[9], [29], [34], [35]
Mixed Integer Quadratic Programming		[7]				
Least-Squares Support Vector Machine					[38]	
Lagrangian Relaxation	[18]					
Interior Point Method	[15]					
Dynamic Programming	[13]					[37]
Deterministic Programming						[33]
Stochastic Programming				[22]		[9], [30], [33], [34],[35], [36]
Mixed Integer Stochastic Programming						[27]
Robust Programming	[15]	[19]				[32], [33]
Game Theory						[9], [32]
Real-time Optimization						[26]
Statistical Modeling	[16]					
Heuristic & Meta-heuristic Algorithm	[17]		[20], [23]			[25]
Multi-Market Optimization Model			[21]			
Optimal Power Flow Model	[14]					

in the electricity market while outlining the main advantages and disadvantages for EV owners and some policy implications. This paper also showed that financial motivation could play an influential role in augmenting the participation of EVs in technical services to the electric power grid. In [17], a market mechanism aimed at using EVs to improve the power grid reliability was proposed. In that work, the participation of EV owners in the proposed market mechanism depends on financial discounts on the SmartPark program charging cost. The optimal incentive value is critical in this model as it directly affects the market participation of EVs. In reference [18], an electricity pool market participation of flexible demands, EVs and electric heat pumps, was modeled for an aggregator. The paper combined a centralized scheme with a decentralized structure of demand participation through dynamic pricing mechanisms.

Aggregators can contribute significantly to various regulation services while leveraging the benefits of vehicle-to-grid (V2G) operation modes. Reference [19] proposed a two-stage hierarchical optimization modeling for an EV aggregator to solve the day-ahead operation problem, which considers both charging and discharging scenarios for EVs. These stages consider the maximization of the aggregator's total profit as well as the uncertain EV driving patterns, battery degradation of EVs through the charging and discharging modes, and the power distribution network limitations. The resulting model is a single-level problem that is modeled through mixed-integer linear programming (MILP). The output of that decision-making model is the amount of power bought from or sold to in the day-ahead power market. Ref. [7] presents a simultaneous pricing and bidding mechanism designed for an EV aggregator to participate in a wholesale power market. A two-level optimization structure was proposed considering a bidirectional power flow operational framework. The upper-level problem aims to maximize the aggregators' profit. In the lower level, the EV owners' utility is maximized. The original bi-level problem was converted into a convex quadratic programming model, and solved by commercial optimization solvers.

2) Day-Ahead and Real-Time Wholesale Energy Markets

Several works studied the participation of aggregated EVs in both day-ahead and real-time energy markets. The optimization model developed in [20] showed EV's capability to participate in the electricity balancing market during several time periods as part of its regulation effort. In [21], a mathematical multi-market optimization model is proposed for participation of aggregated EVs in sequential day-ahead active power and frequency regulation markets, which is based on the real-time prices and market mechanism. That method is modeled by a two-stage optimization algorithm in which the EVs energy dispatch is performed through a hierarchical control framework.

The work in [22] demonstrates the benefits to EV users when the charging control is given to an aggregator. The aggregator aims to maximize the total number of EVs in the EVCS during the flexible periods and compensate EV owners by reducing their overall charging cost. With a well-established coordination between the energy markets and EV owners, an EV aggregator can participate more effectively in both the day-ahead and real-time markets to provide energy to all EVs.

It is important to highlight that EV aggregators can be for-profit or non-profit entities. For-profit aggregators can make profit by purchasing cheaper energy in the wholesale market in order to sell it to EV owners/charging stations at a higher price. On the other hand, non-profit aggregators are mainly focused on reducing the overall procurement cost. In [23], a MILP model was proposed to obtain the most profitable charging schedule of for-profit EV aggregators while considering their participation in both the day-ahead and real-time markets. This work presented an optimized scheduling approach for EV charging in real-time with energy storage systems by including the bidirectional communication between an EV aggregator and the power grid. This research has paved the way to a more balanced load distribution of charging while contributing to aggregators' profit.

B. Participation of EVs in Wholesale Energy and Ancillary Services Markets

Several studies have modeled the optimal EV participation in ancillary services markets together with the energy markets. A business model framework for EV aggregators to participate in both markets is presented in [24]. The study considered the value chain consisting of proposition of the value, creation of the value, and delivery of the value that helps EV aggregators to get better informed about the business structure of smart charging and participate in energy and ancillary service markets. Ref. [25] studied the direct involvement of EV aggregators in the ancillary services considering a virtual power plant (VPP) model able to reduce the overall load on the dispatch center. Through that model, EV aggregators can optimize their profit by forecasting the bidding curves of other aggregators. EV owners, on the other hand, can maximize their profit by utilizing the developed pricing strategy based on their usage and charging demand.

A user-preference mechanism was applied in [26] to allow the direct participation of an EV aggregator in ancillary services markets. This work aimed to help EV owners participate in secondary frequency response in an aggregated mode and through a V2G approach. In reference [27], a bidirectional charging-discharging framework was proposed to allow EV aggregators to provide capacity and energy regulation. The optimization methodology was modeled using MILP to ensure the global optimality. Uncertainty, driving pattern, constraints regarding state of charge (SoC) of EVs' batteries, capacity, regulation demand as well as offer, and power system security are applied to the problem to consider the factors that most affect the profitability of the EV aggregator.

Ref. [28] proposed an optimal management and control scheme for EV aggregators to help them participate in day-ahead energy markets as loads with the possibility of bidding in reserve markets. The procedure was based on a bidirectional monitoring and data exchange through a smart grid paradigm environment. Ref. [29] developed a decision-making framework to help an EV aggregator attain the maximum monetary profit while participating in both the energy and reserve markets. The EV aggregator aims to reimburse EV owners for their battery deterioration due to the additional activity while participating in the reserve market. Alipour et al. [30] presented a scheduling mechanism for EV aggregators in energy and reserve markets. This model maximizes the aggregators' profit through charging in low-price timespans together with the ancillary service availability proposition. A stochastic programming framework was employed to effectively deal with uncertainties pertaining to market prices and EV availability.

To participate in day-ahead markets, such as reserve or up/down regulation markets, a forecast is needed to estimate the amount of energy to be dispatched. Since these market-related signals are not generally known in advance, some studies considered expected values for the power to be injected to the grid from the EVs as a function of a preferred operating point (POP) [31] to keep the EVs charging/discharging rate to fluctuate around their own POP [9, 31]. A bi-level optimization modeling formulated in the form of mathematical programming with equilibrium constraints (MPEC) was presented in [9] to find an optimal bidding operational strategy for EV aggregator's participation in day-ahead energy as well as ancillary services markets. The method used the POP curve to control the aggregated charging power to participate in the regulation market. This work proposed a stochastic programming model to tackle the uncertainty characteristics of the problem coming from EV fleet behavior, load, RE production, and generation and transmission lines outages. These uncertainties were then applied to a Monte Carlo simulation for scenario generation, and Conditional Value-at-Risk (CVaR) was integrated to measure risks coming from those uncertainties. A V2G framework for an EV aggregator was developed in [31]. The framework was designed to help the aggregator optimize the EV charging/discharging mechanisms to participate in demand response markets and providing load regulation and spinning reserve. To this end, they used a power draw expected value as a function of their POP besides the value pertaining to up and down regulation scenarios and the responsive reserves.

A leader-follower game method modeling an EV aggregator and EV owners was introduced in [32] to find the optimal charging and scheduling of frequency reserve. In order to properly manage the regulation signal uncertainty, a data-driven and a robust optimization approach was employed. Three methods of deterministic, stochastic, and robust programming for EV charging/discharging scheduling to participate in day-ahead energy and ancillary service markets were all presented in [33]. The main aim of this work was to better model the uncertainty pertaining to the reserve activation, known as balancing energy procurement within the European context, which together with the EVs availability, can affect considerably the applicability of EV aggregators participation in day-ahead electricity markets. An innovative methodology was proposed for the uncertainty of reserve activation. As it is demonstrated in this work, due to the considerable extent of uncertainty, the deterministic model cannot tackle applicably with the problem. However, the other two methods, the stochastic and robust programing, were better able to cope with the uncertainties, and simulate the problem more precisely.

In [34], the participation of an EV parking lot (EVPL) in a DRP was studied considering price-based and incentive-based mechanisms. The simulations demonstrated the impact of plug-in EVs (PEVs) participation in the profit margin earned by EVPLs in the DRP. Similarly, Ref. [35] investigated the financial profitability aspect of an EVPL using the considerable storage capability of connected PEVs to provide energy and reserve services to the power grid through the wholesale electricity market. The market participation of EVPL considered both the grid-to-vehicle (G2V) and the V2G operations. That study showed that the EVPL participation in the reserve market increased its profits when compared to the energy market. Ref. [36] studied the impact of EVPL location considering its direct participation in the electricity market. The analysis demonstrated that the EVPL profit increased proportionally with EV penetration.

Ref. [37] discussed the power system reliability assessment considering the stochastic behavior of EVs in terms of mobility. The EV participation in a ramp market was considered in different scenarios. Ref. [38] studied the optimal participation of EV aggregators in a valley-filling ancillary service market while considering the CVaR model to calculate the required energy storage capacity to ensure the maximum return. It showed that EV aggregators can significantly increase their revenues by effectively participating in ancillary services markets.

III. Future Directions

The successful participation of EV infrastructure in multiple electricity markets will depend on critical analysis or advances in technical, economic, social, environmental aspects. Select research directions for future works are presented and discussed in the following subsections.

A. Analysis of Economic Benefits to All Market Participants

Many recent works in the literature demonstrated the benefits of EV market participation from the viewpoint of grid operators and for-profit EV aggregators. Further research should be conducted to analyze the specific economic benefits for nonprofit EV aggregators as well as single EV owners, EVCSs, and EVPLs. The studies, so far, can be considered as the first steps in aggregated market participation of EVs. To have a well-performed participation of EVs in power markets, on the other hand, it is necessary to take all participants into consideration. There is a supply chain of participants who need to find enough profits of working within the structure through which the aggregated form of EVs can efficiently participate in wholesale power markets in terms of charging the EVs and/or providing services to the power system. The overall charging cost reduction along with the introduction of market incentives can motivate greater participation of EV, EVCS, and EVPL owners and aggregators in the electricity market. Furthermore, these incentives can also stimulate greater EV adoption for transportation purposes and help reduce GHG emissions.

EV aggregators can be formed in various structures. It can be a single EVCS or EVPL or a combination of multiple agents. An EV aggregator can also make contract with EVCS and EVPLs or working in cooperation with them. Regardless of the EV aggregators' structures, their interactions with the other separate entities and participants should be considered in future studies. In other words, further research should be conducted to analyze the specific economic benefits of single EVCSs or EVPLs as well as single EV owners.

B. Infrastructure Planning for Market Participation

EVCSs and EVPLs play a pivotal role in enabling greater EV adoption worldwide, from both the power and transportation system perspectives. One essential prerequisite concerning the transportation system is the widespread availability of charging stations. A well-organized number of EVCS in a wide range of area helps to mitigate the anxiety regarding travel range and time of charging. Furthermore, enough amount of charging facilities for EVs within parking lots can encourage usage of EVs in respect of comfortably and time-usage optimality. Both EVCS and EVPL are related to the power system operation and planning scheduling concerns in terms of whether unidirectional or bidirectional operation modes.

Based on the infrastructure planning point of view, existing research works, in most cases, focused solely on EV market participation of the existing EVCS and EVPL infrastructure. Further research should particularly investigate the optimal placement and sizing of new EV charging infrastructure while taking into account their direct participation in multiple electricity markets. More specifically, those future works should consider the impact of EV market participation on the net present value, payback time, and rate of return of different types of EV charging infrastructure. Considering all these practical aspects at the same time through the techno-socio-economic sitting and sizing planning of EVCSs and EVPLs with a view to working as a sole EV aggregator or within a larger one can release the potentials of those infrastructures and ease the participation process of stakeholders' investment on the EV charging/discharging infrastructures.

C. Market Participation through Home Charging Facilities

Several works reviewed in this paper considered the market participation of public infrastructures. However, aggregated home or private charging can also be leveraged to provide services for EV owners and buildings through building-to-vehicle (B2V) and vehicle-to-building (V2B) modes, respectively. Expanding the well-organized infrastructures for V2B and B2V scenarios attracts more vehicle owners to use EVs and correspondingly, more influential one- or two-way power exchange can be introduced for the aggregated power market participation. Aggregated EVs can effectively participate in wholesale energy, real-time, and ancillary services markets in terms of demand response programs, as flexible loads, and power provision, as battery storage devices or DERs, considering the battery degradation modeling. Further research is needed to develop efficient market mechanisms to facilitate aggregated B2V and V2B operations. Blockchain and smart contracts are some potential approaches that could be used to facilitate a large number of transactions and technical operations while ensuring the security and privacy of all market agents.

D. Simplification of Market Participation for Single EVs

Simplified and effective regulations regarding EV owners' involvement in aggregated charging and power system services provision have a determining role in the practical widespread market participation. One of the main advantages of having EV aggregators as interfaces between ISOs and the EV owners is to make the practical techniques related to both the power system and power market sides simplified enough to be easier, faster, and more used by EV owners who are not professional power market participants. Too many or fast-changing economic-based remarks, high-level technical regulations, and opposing standards have negative impacts on the aggregated market participation of EVs, which might then need to take some major steps on neutralization of side effects including deregulation procedures. Well-designed regulations for EV owners, however, not only can release the potentials of EV market participation, but also has a significant direct influence on EV usage expansion planning affecting the power system, the transportation system, the environmental ecosystem, to name but a few. More practical studies and research considering sensitivity analysis of socio-behavioral indices besides to techno-economic factors are needed in this respect.

IV. Conclusions

The electrification of the transportation sector can contribute to greater sustainability, reduced GHG emissions, and larger options for providing essential energy and ancillary services to power distribution and transmission networks. However, the effective grid integration of EV charging infrastructure will depend on the development of innovative and efficient electricity market mechanisms for EV owners and aggregators, including EVCSs and EVPLs. This paper has presented a brief survey of the existing research works on electricity market participation of EV infrastructure. The existing research works were divided into two main groups: 1) studies that considered day-ahead and real-time energy markets, and 2) studies that considered ancillary services markets. Different models and strategies have been outlined, and future research directions have been presented and discussed.

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