


Review

# An Updated Review and Outlook on Electric Vehicle Aggregators in Electric Energy Networks

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**Abstract:** Electric vehicles (EVs) are predicted to be highly integrated into future smart grids considering their significant role in achieving a safe environment and sustainable transportation. The charging/discharging flexibility of EVs, which can be aggregated by an agent, provides the opportunity of participating in the demand-side management of energy networks. The individual participation of consumers at the system level would not be possible for two main reasons: (i) In general, their individual capacity is below the required minimum to participate in power system markets, and (ii) the number of market participants would be large, and thus the volume of individual transactions would be difficult to manage. In order to facilitate the interactions between consumers and the power grid, an aggregation agent would be required. The EV aggregation area and their integration challenges and impacts on electricity markets and distribution networks is investigated in much research studies from different planning and operation points of view. This paper aims to provide a comprehensive review and outlook on EV aggregation models in electrical energy systems. The authors aim to study the main objectives and contributions of recent papers and investigate the proposed models in such areas in detail. In addition, this paper discusses the primary considerations and challenging issues of EV aggregators reported by various research studies. In addition, the proposed research outlines the future trends around electric vehicle aggregators and their role in electrical energy systems.

**Keywords:** electric vehicles (EVs); electric vehicles aggregator (EVA); electrical energy systems; demand side management; energy saving



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## 1. Introduction

Modern transportation systems all over the world face considerable and substantial challenges due to climate change and limited sources of fossil fuels because of environmental and economic issues [1,2]. Electric vehicles (EVs), which have strongly penetrated in power and transportation sectors, are predicted to significantly emerge as alternative vehicles for the existing transportation system in upcoming years [3]. Due to rising fossil fuel prices and associated environmental concerns, EVs are seen as a viable alternative to conventional automobiles, and it is anticipated that their use will soon skyrocket. However, there will be several practical and technological challenges associated with the widespread use of EVs and their extensive integration into the energy system [4]. The integration of EV batteries into the electric networks provides possibilities of purchasing power from the grid as a load or transferring power to the grid as an energy source [5]. Accordingly, there are good motivations for developing EVs, including economic benefits, environmental advantages, energy security, and costs associated with oil consumption for transportation [6]. The researches in the area of EVs include optimal control strategies of EVs [7,8], investigation of the effect of EVs in electric power networks [9–11], frequency control of power systems in the existence of EVs [12,13], the proposal of various storage systems for EV batteries [14,15], power market analysis in the presence of EVs [16,17], allocation of EVs

parking lots [18,19], modeling and forecasting EV demand [20,21], the effect analysis of EVs from an environmental viewpoint [22,23], and the optimal planning issue of power systems in the presence of EV charging stations [24,25].

The high penetration of distributed generation and electrical energy storage systems in power systems have created principal changes in such systems. Power system regulators and operators tend to prepare a condition for participating in demand-side management programs in energy markets [26]. The electric vehicle aggregator (EVA), which was introduced due to the large-scale introduction of EVs, can be introduced as an agent between the EVs and the electrical energy systems and has sufficient flexibility for participating in demand-side management. Consumers could not participate individually at the system level for two key reasons: (a) They generally do not have the necessary level of individual ability to participate in electricity system markets, and (b) there would be many participants, which would make it challenging to regulate the volume of individual transactions. An aggregation agent would be necessary to simplify interactions between consumers and the electricity system. The main responsibility of the EVA is to manage, charge, and purchase electricity for vehicles. The EVA takes advantage of obtaining additional revenues from participating in the energy market and charging cost decrements to EV owners. In other words, the EVA is considered a large source of a power production unit or load from the system operator's point of view, which coordinates ancillary services such as spinning and regulating reserve.

Recently, several review papers have been published on the application of EVs in electric networks. In [27], the authors intended to give an overview of current EV control structures in charging stations, EV management goals in power systems, and EV charge and discharge management optimization approaches. In this study, the goals that can be achieved with the effective charge and discharge management of EVs are separated into three groups of network activity, economic, and environmental goals and examined. The authors in [28] have investigated managed EV charging, giving a broad overview of its current implementations and costs in the United States, critically evaluated the methodologies used in studies that analyze and model data, and quantified the costs and advantages of managed charging. The market for EV charging infrastructure is examined in [29] with a focus on the various charging methods already in use, the key market players and their primary roles, and the upcoming regulatory requirements for wide-scale expansion. The authors have studied the impact of EVs in distribution networks in [30] based on driving patterns, charging characteristics, and vehicle penetration. The combination of EVs, renewable energy sources, and electrical energy systems have been reviewed in [31], where EVs' economic, environmental, and grid aspects have been discussed. The investigations have shown that wind energy is more effective in integrating EVs, where unwanted wind energy can be considered an energy source for charging EV batteries. In [32], a comprehensive review has been prepared on different smart charging concepts and strategies for EVs, where practical projects all over the world have been presented. The authors have reviewed various charging strategies for EVs and studied major requirements, advantages, and challenges of vehicle-to-grid (V2G) systems in [33]. In [34], the effects of uncertainty parameters in studying the decision-making of EV aggregators in competitive markets are investigated to maximize the aggregator profit and minimize the payments of EV owners and are studied as a bi-level problem. The published research on the current status and effect analysis of V2G technology on electric distribution systems have been reviewed in [35]. A stochastic bi-level scheme for EV aggregators in a competitive environment is proposed in [36], where the participation of the aggregator in day-ahead and balancing markets are studied to maximize its expected profit. In addition, researchers have introduced the requirements, challenges, benefits, and various strategies for V2G interfaces. Moreover, different review papers have been published around battery degradation and instantaneous charge/discharge models of EVs [37], financial analysis of purchase incentives for the EVs owners [38], various approaches proposed for EVs usage modeling [39], the coordinated operation of the distribution network and EV aggregators [40], and different frameworks

introduced for the optimal design of EVs systems [41]. Remarkable efforts have been made around EVAs in recent years due to the positive effect of such aggregators in demand-side management.

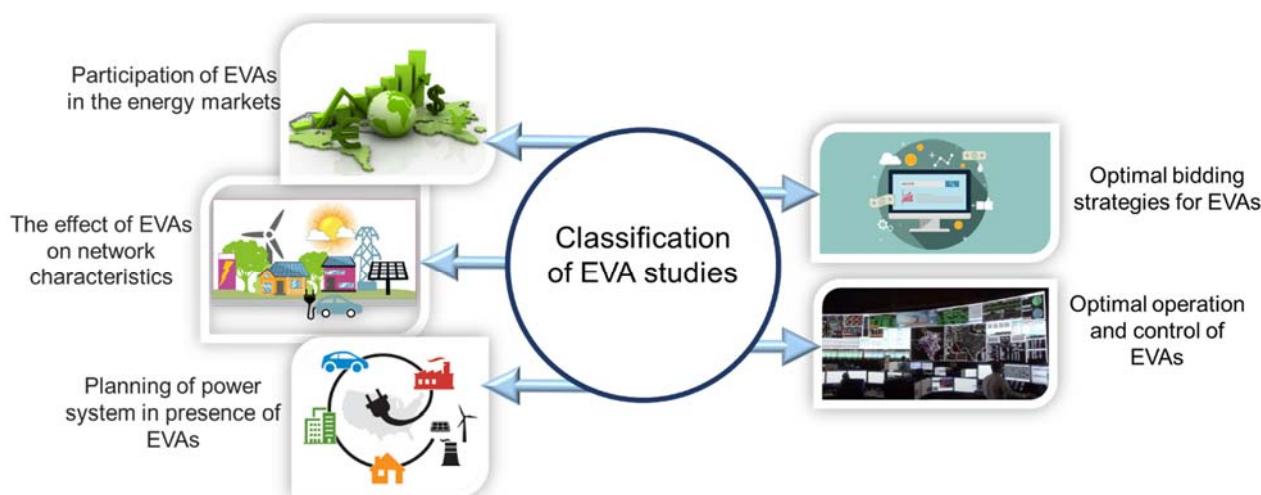
According to the analysis of the literature that was just completed, most of the publications explain the broad idea behind EVs charging management and operations in energy systems. There is a lack of condensed advanced literature, which contains information on EV aggregation fundamentals, advantages, techniques, and forward-looking recommendations. To the authors' best knowledge, no review paper has been published on EVAs and the different challenges of such aggregators in electrical energy systems. This study aims to overview the current literature around the application of EVA in electric energy systems. The existing literature and most contributions of the published research have been proposed with recommendations for future trends. In comparison to the literature that has been presented, this work makes the following detailed contributions:

- In this work, the most recent findings on the study of EVA in energy systems and management techniques for EV applications are reviewed.
- The authors have discussed the literature around EVA challenges regarding participation of EVAs in energy markets and their role, bidding strategies in energy markets, the effect of EVAs on energy system characteristics, and the planning of power systems, considering the integration of EVAs.
- This work has discussed the comparative criticism of the recently proposed EVA models for operation in energy systems and markets.
- This study offers the research gaps and future research guidelines based on comparative critiques.

The remainder of this paper is organized as follows: Section 2 reviews the current literature with various contributions and main findings of research papers around EVAs. Future trends are presented in Section 3 to recommend novel ideas and research gaps and future guidelines around EVAs. Finally, the paper is concluded in Section 4.

## 2. Literature Review and Detailed Discussion

This section aims to study the main research areas on EVAs, focusing on the main contributions and a detailed discussion. Different research studies have been investigated in recent publications around EVA, which are demonstrated in Figure 1.

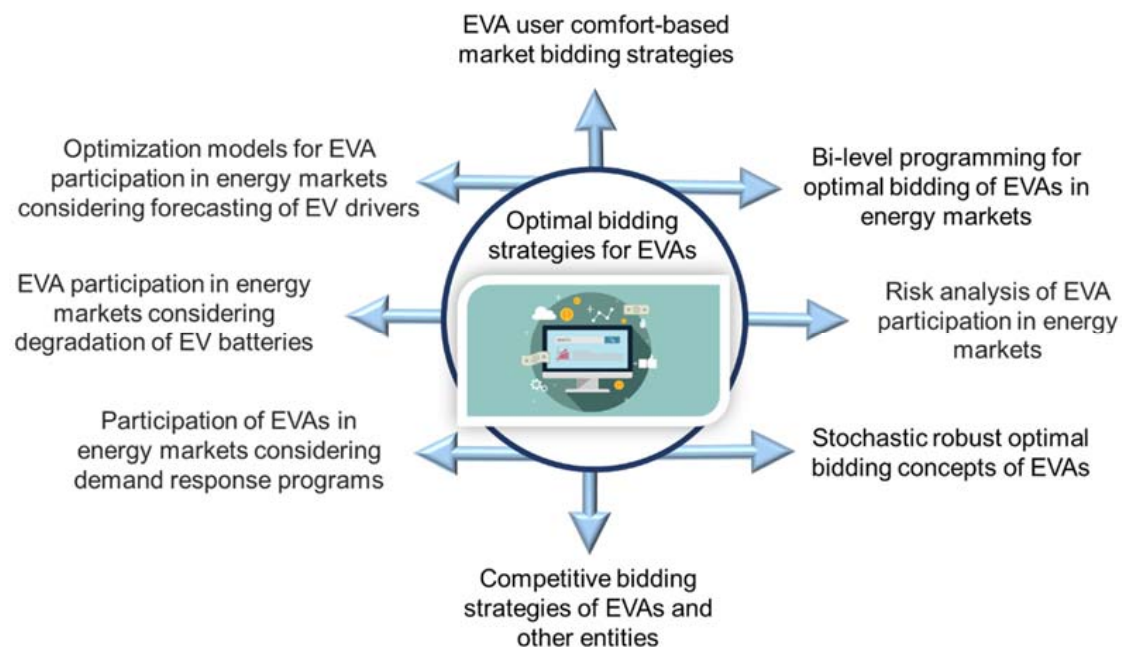


**Figure 1.** Different research studies published around EVAs.

### 2.1. Optimal Bidding Strategies for EVAs

The capability of the participation of EVAs in the day-ahead energy and energy markets provides the opportunity of obtaining profits by proposing an optimal bidding strategy. A comprehensive viewpoint of optimal bidding strategies for EVA is demonstrated in Figure 2.

The main contributions around optimal bidding strategies for EVAs contain uncertainties of market bids, driving patterns, and forecast errors of driving behavior based on stochastic and robust schemes and risk analysis of optimal bidding strategies. In addition, energy and secondary reserve bidding strategies, demand response exchange (DRX) market, and decentralized balancing opportunities are studied around bidding strategies for EVAs.



**Figure 2.** Optimal bidding strategies for EVAs from different viewpoints.

Table 1 gives a summary of recently published papers around optimal bidding strategies for EVAs from different viewpoints, considering their main contributions, considerations, and research gaps.

**Table 1.** A summary of recently published papers around optimal bidding strategies for EVAs from different viewpoints.

Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[42]	EVA user-comfort day-ahead and reserve market bidding	Uncertainties of EV drivers' behavior, comfort of EV drivers within participation in electricity market.	Sharing revenues and prioritizing charging through bilateral agreements between EV owners EVAs	2020
[43]	Optimal bidding strategies of EVAs based on indirect load control in day-ahead markets	Bilevel programming, application of exact relaxation concept for handling constraints of the problem	Computational time analysis for large case studies	2022
[44]	EVA bidding strategies based on game theory presence of wind power producers	Risks arising from imbalance wind power-EV, study of EVAs in regulation, balancing, and day-ahead markets	Competition of EVAs with other entities like DR aggregators	2022

Table 1. Cont.

Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[45]	Multi-stage stochastic modeling of EVA bidding strategies in energy markets	Continues grouping and regrouping aggregated EVs based on their departure time	Consideration of the uncertainties associated with the departure time of EVs	2022
[46]	Competitive bidding strategies of EVAs and wind power plants	Bilevel programming and stochastic optimization	Computational time analysis for large case studies	2021
[47]	Competitive bidding/offering strategies of EVAs and wind power generators	Risk analysis based on conditional value at risk method	New entrants can be taken into consideration for their higher potential competitiveness in the power market, influence of reserve provision and energy market arbitrage on wind turbine failure	2022
[48]	Optimal bidding strategies of EVAs considering fast charging stations	Risk analysis of charging demands and power market prices based on conditional value at risk method	Coordination of EVAs with optimal pricing of EV charging	2020
[49]	Collaborative Optimal bidding strategies for various intermittent resources including EVAs and renewables	Risk analysis based on a novel distributionally robust optimization concept	Computational time analysis for large case studies	2020
[50]	Multi-time scale optimal bidding strategies of EVAs	Estimation of EVs degradation cost on a 5-min time scale	Consideration of the uncertainties associated with the arrival/departure time of EVs	2020

The optimal bidding strategy of EVAs in the day-ahead power market has been studied in [51] to obtain the minimum charging cost of EVs, meeting their flexible demand. Accordingly, bi-level programming has been proposed for the bidding strategy, where the charging cost of EVAs has been minimized at the upper level, considering the power constraints of EVs. In addition, the lower level handles the market clearing process, where the bidding of other participants of the market is not based on the aggregator's bidding behavior. Similar research has been accomplished in [52], where the optimal day-ahead bidding framework has been proposed for EVA to minimize the charging cost of EVs without considering the capability of V2G. The bi-level programming is introduced for studying the charging cost at the upper level and market clearing at the lower level. In this study, the uncertainties of market bids and driving patterns have been considered in the proposed model, which aimed to provide optimal bid volumes and prices. A stochastic, robust optimization framework is proposed in [53] for an optimal bidding strategy of EVA, considering uncertain parameters of the problem which include power prices and driving patterns of the EV drivers. Optimal bidding of EVA in the day-ahead electrical energy market has been studied in [54,55], using two alternative optimization concepts, which include global and divided concepts. The global and divided methods utilize aggregated values and individual information from each EV in solving the problem, respectively. After determining the optimal bidding, the operation management is accomplished to define the deviation between the accepted bids and consumed electrical energy by EVs. In [56], the authors have proposed optimal manual reserve bidding of EVA, where day-ahead and hour-ahead operational management concepts are introduced. In this research, forecast errors associated with driving behavior and characterization of information by individual

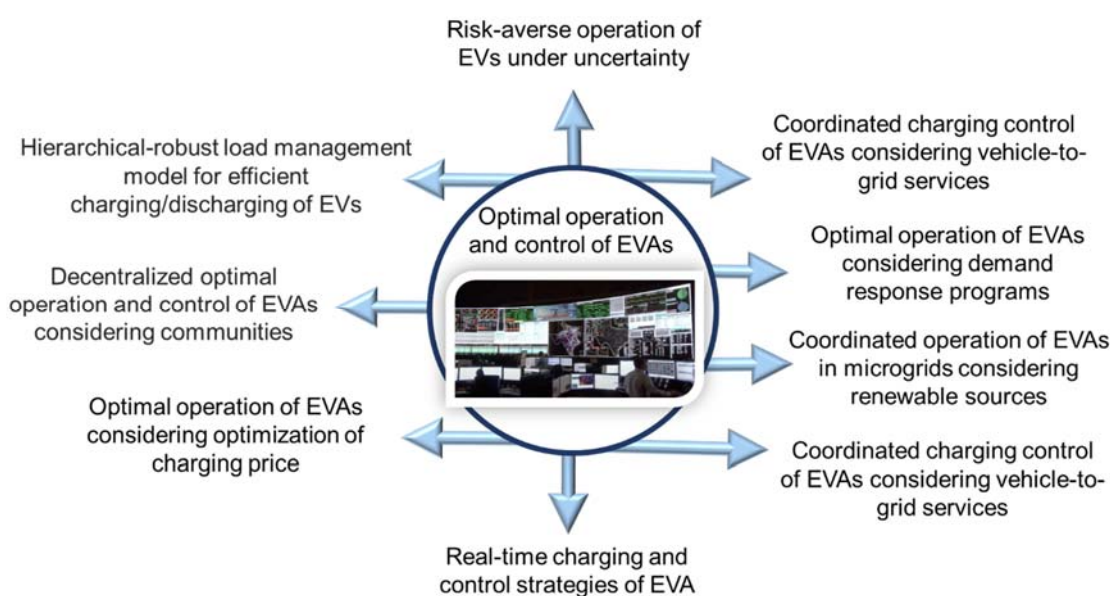


EVs are studied. The proposed operational management concepts are effective in reducing deviation costs and ensuring a reliable transfer of manual reserve. A novel day-ahead optimization framework between energy and secondary reserve bidding strategies has been proposed in [57], where a new operational management method is introduced based on characteristics of the secondary reserve for minimizing differences between contracted and realized values. The proposed method in this study considers the possibility of offering a reserve band in both upward and downward directions. The authors have studied the optimal bidding strategy of EVAs in the energy market and various regulation reserve markets [58]. In addition, the degradation cost of EV owners has been considered in the proposed model. The voluntary reserve markets with price-quantity offers are studied by proposing a realistic concept. The proposed strategy has a risk-averse characteristic, where the probability of acceptance and up- and down-regulation are considered. The participation of EVA in day-ahead and intraday power markets has been investigated for the demand response exchange (DRX) market in [59]. So, the authors have presented a multi-stage stochastic approach to attain optimal performance of the aggregator by studying the EV minimum connection duration (MCD) and uncertainties of market price, driving patterns of EV drivers and activated quantity of reserve. A new market agent taking part in the power market on behalf of a wind plant owner and an EVA is introduced in [60], playing the role of the prosumer. The prosumer co-optimizes the energy supply offers and demand bids for increasing the profit of the wind energy producer and EVA by obtaining optimal management. A decentralized balancing opportunity is provided by the proposed model, which balances the extra energy generated by wind units and real-time increase in the EV consumption rate. In [61], the authors have proposed a stochastic model for the optimal bidding strategy of EVAs in day-ahead energy and regulation markets, considering market conditions and characteristics of an EV fleet. Accordingly, stochastic linear programming is proposed to study and investigate the systematic treatment of the instructed and uninstructed energy deviations, considering the system operator or EVAs as responsible, which plays a significant role in the bidding strategy of the aggregators. A risk-based optimal bidding framework is proposed for the participation of day-ahead energy and ancillary services in [62] using Monte Carlo Simulation (MCS). The uncertainties associated with EVs forecast errors, load, power supply of wind turbines, and production units, and the risks that appeared as a reason for uncertainties are handled utilizing conditional value at risk (CVaR). In [42], an optimal bidding strategy for EV aggregators is proposed based on a paradigm in which it offers/bids for the day-ahead (DA) and secondary reserve markets to reduce total cost. Furthermore, concerns linked to EV owners' behavior and market prices are addressed by using stochastic scenarios with real data. An optimal bidding technique for an EV aggregator engaging in day-ahead marketplaces is investigated in [63], where based on the real need of the EV user, two typical agent modes between the EV aggregator and the EV user are introduced, namely the centralized protocol management mode (CPMM) and the decentralized demand response mode (DDRM). In [64], for charging electric vehicles, a power price management technique is proposed based on the bidding strategies of EV aggregators in the real-time energy market. In this study, the batteries of EVs are managed centrally by aggregation managers who take into consideration the grid's limited power supply during peak electricity usage and adjust the demand for charging through electricity pricing regulation. Under market uncertainty, the authors in [65] provided an optimization model for determining day-ahead inflexible bidding and real-time flexible bidding. The suggested EVA optimum bidding model, which is based on the link between market price and bid price, tries to minimize the conditional expectation of electricity purchase cost in two markets while taking price volatility into account. The authors in [66] provided a strategic bidding model for a group of price-taker plug-in EV aggregators that share a distribution network and compete in both day-ahead energy and ancillary service (i.e., up/down-regulation reserve) markets. In [67], a new EVA coordination strategy is proposed for handling various self-interested EVAs, applying the price-maker bidding method. The proposed model coordinates bids offered by aggregators

in the day-ahead electricity market for achieving reduced costs. The proposed coordination method scales linearly with fleet size and the number of EVAs participating in the electricity market, which makes it capable of dealing with arbitrary, large systems.

## 2.2. Optimal Operation and Control of EVAs

The capability of supporting EVA operation by the existing grid infrastructure and technology can be introduced as an advantage of grid-to-vehicle power. Figure 3 shows a general viewpoint of research studies around the optimal operation and control of EVA. The main contributions of research around the optimal operation and control of EVAs contain uncertainties associated with market prices and EVs behavior, risk-averse scheduling, and studying the subject considering the penetration of renewable energy sources. Additionally, the adoption of model predictive control based, interruptible load (IL), and the analysis of power losses are examined in recent studies.



**Figure 3.** The optimal operation and control of EVA in different viewpoints.

A summary of recently published studies on the optimal operation and control of EVAs is provided in Table 2, along with a discussion of the papers' primary contributions, limitations, and research gaps.

**Table 2.** A summary of recently published papers around optimal operation and control of EVAs.

Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[68]	Decentralized optimal operation model of energy hubs and EVAs	Uncertainties of power market prices and EV drivers' patterns	Networked constrained optimal operation of energy hubs and EVAs as well as V2G mode	2021
[69]	Multi-agents based optimal operation of EVAs in microgrids	Power price uncertainties, prediction of domestic loads	Precise forecasting and evaluation of enough amount of data considering uncertain parameters	2022
[70]	Hierarchical-robust load management model for efficient charging/discharging of EVs	V2G and real time and day-ahead energy markets	Consideration of the uncertainties associated with the SOC of the EVs in arrival time	2022

Table 2. Cont.

Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[71]	Optimal robust operation of distribution networks with EVAs	Considering load curtailments and uncertainty of uncertainties in charging demands of EVA	Real-time operation model and uncertainties of other parameters like electricity price	2022
[72]	Hybrid robust-stochastic operation of EVs considering renewables	Uncertainties associated with power price, EV load and renewable power, the effect of battery storage for EV parking lots	Real-time operation model of EV parking lots	2021
[73]	Decentralized coordinated optimal operation of EVAs with V2G services considering objectives of both EVA and distributed generators	Consideration of distribution system operator constraints like power losses and bus voltages	Research on combined effect of network reconfiguration in line with EVAs for analyzing system characteristics	2022
[74]	Energy management concept of EV battery swapping station (BSS)	Participation of BSS in day ahead, real-time, and ancillary markets, a game theory model for incentive-based vehicle-to-vehicle operation	Deployment of the proposed model to large-scale residential communities and industries	2019
[75]	Optimal operation of EVAs based on sac deep reinforcement learning concept	Real-time model of grid-connected EV charging stations	Computational time analysis and consideration of constraints of the energy network	2020

The authors have studied the short-term distribution network scheduling under uncertain conditions in [76], where an ideal robust model is put forth in order to reduce network operation costs. This study used the robust optimization method to handle the pricing uncertainty of the power market.

The authors in [77] presented a novel method for resolving the problem of uncertainty in EV aggregators, in which the uncertainty-based profit function is transformed into a deterministic multi-objective problem with deviation and average profits as conflicting objective functions, with the average profit aiming for the maximum, while deviation profit aims for the minimum. In [78], a robust optimization technique is used to study the robust scheduling of EV aggregators in the face of price uncertainty. The suggested EV aggregator in this study engages in the power market to maximize profit, where the upper and lower amounts of upstream grid prices are employed instead of the forecasted prices to model market price uncertainty with the given technique. The coordination between EV charging stations and EVs is investigated in [79], assuming that they are operated by non-cooperative parties. A mixed integer linear optimization model is used to optimize the operation strategies of EV charging stations, while an integer optimization model provided the best operation strategy for EVs. In [80], a novel mechanism for supplying the system's energy during the operational day is proposed, based on contractual agreements between owners of EVs and the smart microgrid. The suggested approach allows for the integration of EVs parked in official parking lots into the operation of a smart microgrid and the generation of revenue. The major concerns explored in [81] are optimal self-scheduling of EV aggregators, network operation indices, and distribution system operator policies on the aggregator's performance. In an incentive and regulatory structure, the suggested

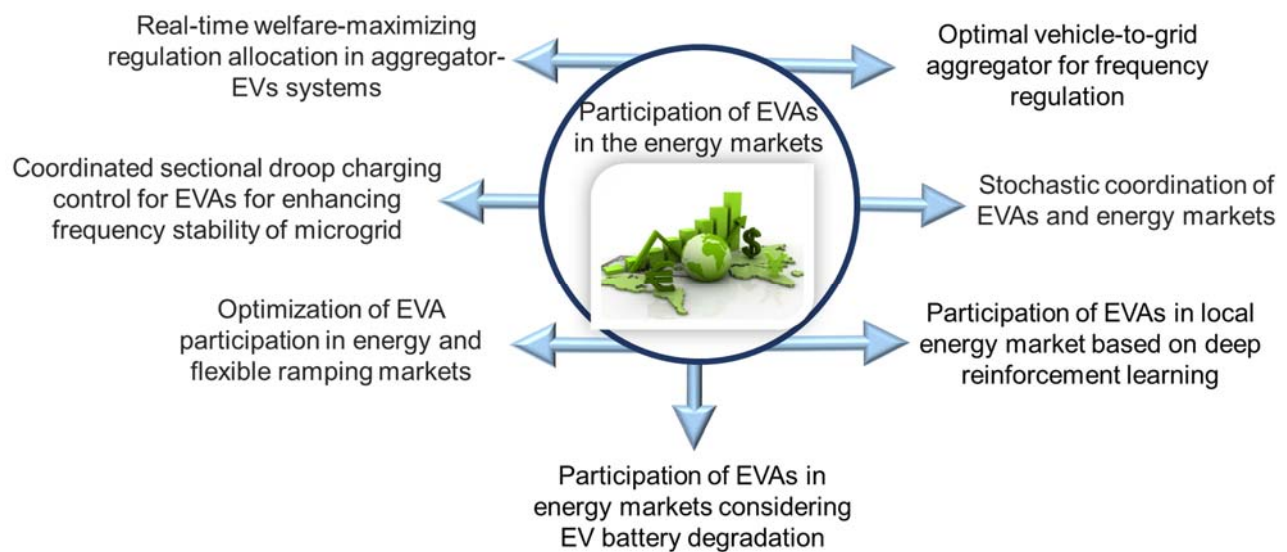


strategy maximizes the aggregator's daily profit by participating in day-ahead and real-time markets and supplying power quality services to the distribution system operator. In [82], the stochastic scheduling of EVAs is presented, considering the uncertainties of power price and EV drivers' collective behavior. The Latin hypercube sampling (LHS) approach and a scenario-reduction methodology are used to create the suggested model. The EVA is expected to be able to engage in both the energy and regulation markets, resulting in profits for both the aggregator and the EVs. The coordinated charging control of an EVA is studied in [83], aiming to minimize the charging cost and reduce power losses that appeared due to fluctuating loads. An approximate dynamic programming model has been proposed in this study for reducing the dimensionality of both state space and control space. The capability of bidirectional power flow between the EVs and the power grid has been considered, which is effective in reducing power loss. The optimal charging control and frequency regulation of EVA have been studied in [84] for minimizing the total cost of several EVs. Accordingly, a model predictive control-based (MPC-based) method is adopted for scheduling the charging and regulation procedure. Such a strategy is effective in obtaining profits for both the individual vehicle and the whole EV fleet. The authors have applied an interruptible load (IL) pricing scheme for studying the charging scheduling of EVA in [85], where the aggregator is responsible to respond the grid load control command. The authors have introduced power-altering charging (PAC) control, which does not require computational efforts and classical iterative concepts for attaining the fair charging of EVs and preferences such as state-of-charge and departure time. In [86], a multi-objective framework is introduced for providing the optimal coordinated operation of microgrids (MGs) with the penetration of renewable energy sources and EVA. Exponentially weighted criterion and compromise programming methods are implemented in this research for solving the problem, where demand response sources are considered for possible cooperation in providing active and reactive power. In [87], the authors have proposed a double-layer charging control model for EVA for the optimal management and scheduling of EVs. The proposed double-layer model minimizes total cost in the first layer, taking demand forecast and wholesale prices into account and allocating the purchasing power to EVs, considering the network constraints. Such a controlling model is effective in the elimination of line overloads, energy losses, and voltage drops. In [88], a new model is proposed for the self-scheduling of an EVA that purchases power in the day-ahead market and presents balancing services for wind power owners. To investigate the uncertainties associated with driving patterns and balancing requirements, a probabilistic virtual battery model for EVs is introduced in this paper. As a result, to deal with uncertain parameters, a scenario-based, robust strategy is used, which is useful in optimum scheduling due to its conservative qualities. In [89], a decentralized framework is proposed for scheduling loads in a commercial building and the charging behavior of an EV in joint conditions. Mixed-integer programming of the Dantzig–Wolfe decomposition method is applied for solving the scheduling problem, where the main goal of building and EVA is to minimize operation costs. The authors have studied three cases in this reference, including (a) demand limitations, (b) a peak demand charge, and (c) an itemized billing strategy with different prices for power selling and purchasing, which provided the effectiveness of the coordination scheme. A mathematical programming method is implemented in [90] with equilibrium constraints for accomplishing the decision-making process of the EVA in several electricity markets. In this study, indirect load control is applied by defining optimal retail prices for EV. The authors have proposed a bi-level model, where retail tariffs and optimal bidding strategies are proposed in electricity markets in the first level, and optimal charging schedules are provided in the second level. The authors have proposed a similar decision-making model in [91], where the main objective is scheduling EVs charging based on profit-optimal prices of the aggregator considering indirect load control. The proposed bi-level model studies retail prices and optimal bidding in the power market at the upper level and obtains the charging scheduling of EVs based on retail prices at the lower level. The aggregator allocates prices for EVs

individually in the proposed model based on local preferences and physical characteristics. The authors in [92] proposed a two-stage linear stochastic approach for the scheduling of EVA in day-ahead and balancing markets while accounting for market pricing and fleet mobility concerns. The CVaR is modeled using a risk-averse characteristic in the suggested framework. In this work, two indexes are proposed: the expected value of flexibility and the expected value of aggregation. In [93], the tending of EVs to participate in the reserve market and contract terms are studied, considering requirements such as required plug-in time and guaranteed minimum driving range. Two novel contract strategies are proposed in this study, including (1) complete elimination of contract requirements and allowance to participate in system services based on the pay-as-you-go concept, and (2) power aggregators to provide V2G-EV contracts, considering consumers with cash payments. The authors have proposed a bi-level participation problem of EVA in the day-ahead market in [94], where the aggregator purchases power in the day-ahead market and offers regulation services. The bi-level model studies the minimization of EV's cost at the upper level and accomplishes the market clearing process at the lower level. Different constraints of participation of EVA have been investigated, including the effect of application of V2G in the regulation market, capacity limitation offers of EVA in the regulation market, and symmetric bids for up- and down-regulation. A model for the real-time charging controllers' design of EVs fleet for cooperation in ancillary services is introduced in [95], considering the capability of bidirectional charging resources. Model predictive control (MPC) is implemented in the proposed model for dealing with future information to achieve accuracy in regulation signals and cycling on the batteries. An MPC controller is utilized to consider efficiency effects and estimation of the state-of-charge of the EV battery in the time steps during the forecast horizon. A stochastic programming strategy for the efficient scheduling of EVAs in electricity and auxiliary service markets is proposed in [96]. The suggested solution addresses the uncertainties connected with power market prices, vehicle availability, and ISO to aggregate calling signals in the reserve market. The optimal operation of micro-grids in the presence of EVA is studied in [97] for optimizing the scheduling of plants, considering several operational and dynamic constraints. The optimal operation of a microgrid, which incorporates energy storage devices and combined heat and power units to supply both heat and power demands, is examined using different interactions between EVA and the MG operator. In [98], dynamic programming is used to optimize the operation of EVA while considering the ability to charge the battery from the grid and renewable energy sources. The suggested model is investigated using two scenarios of renewable energy generation, one with excess power generation and the other without, as well as various electricity price models. The authors in [99] proposed an active distribution network management technique based on a multi-period optimal power flow model, which includes generating curtailment and intelligent EV aggregation. This study uses coordinated economic optimization for the generation management of renewable energy sources and EV management. EV behavior data is generated using Monte-Carlo simulations, and the aggregated EVs are charged and discharged using an intelligent, orderly controlling model.

### *2.3. Participation of EVAs in the Energy Markets*

Currently, most of the energy market services are carried out by generators bidding into the market. Considering that an EVA includes hundreds or thousands of vehicles with small-scale power, the energy service of large-scale power can be accomplished by such agents. A general overview of the participation of EVAs in the energy market is provided in Figure 4. The main objectives in the area of participation of EVAs in the energy market include stochastic optimal coordinating of charging and regulation, economic and technical analysis of participation of EVAs in the energy market and providing optimal contract size in regulation through application of EVAs.



**Figure 4.** The participation of EVs in the energy markets from different viewpoints.

Table 3 provides an overview on participation of EVs in the energy markets, along with a discussion of the main contributions, constraints, and research gaps/future trends of the research studies.

**Table 3.** A summary of recently published papers around participation of EVs in the energy markets.

Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[100]	Participation of EVs in local energy market based on deep reinforcement learning	Data analytics, asynchronous learning framework	Application of the proposed model on a large case study	2021
[101]	Participation of EVs in power grid frequency regulation	Coordination of hydro power plants with EVs	Analysis of the comfort of EV drivers participating in EVA contracts	2022
[102]	Participation of EVs in energy and regulation markets considering EV battery degradation	Cost-benefit analysis of EVs based on potential revenues	Bidding of EVs in markets and management of charge/discharge of EVs	2022
[103]	Primary frequency control through EVs participation in energy markets	EV characteristics considerations including charger topology, limitation of drive power, and operational modes	Consideration of uncertainties associated with EV drivers' behavior	2022
[104]	Robust modeling of Under-frequency load shedding requirements to ensure frequency stability	Uncertainties associated with wind power EVs patterns	Load restoration strategies of EVs during load recovery	2022
[105]	Application of EV batteries in grid regulation to maintain grid stability	Voltage and frequency control consideration as ancillary services, fluctuations of the renewable sources	Consideration of uncertainties associated with EV drivers' behavior	2021

Table 3. Cont.

Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[106]	Analysis of EVs role in peak shaving, frequency regulation, and spot market trading	Proposal of model predictive control concept and degradation cost analysis	Management grid congestion or supplying reactive power through V2G services	2019
[107]	Optimization of EVA participation in energy and flexible ramping markets	System uncertainties including the power market price and EV drivers' patterns	Real-time analysis and analysis of the role of battery degradation cost	2020

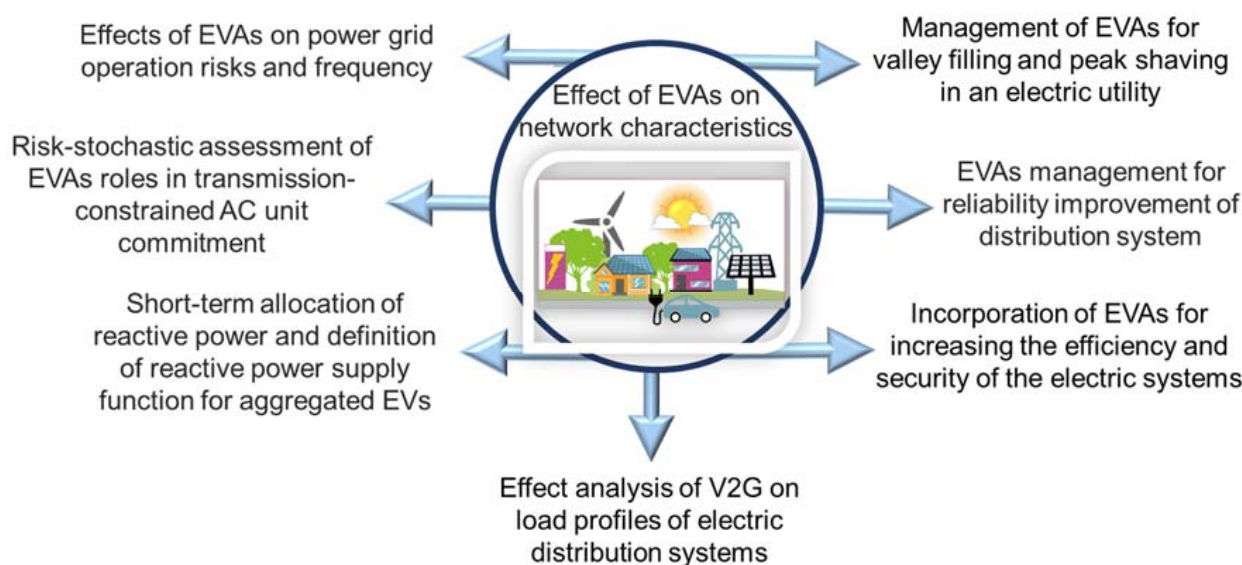
The authors have studied the optimal design of the V2G aggregator in [108], concentrating on frequency regulation by the optimal control strategy of EVs. Dynamic programming is employed for obtaining the optimal charging control, and the relationship between the final state of charge (SOC) control and total revenue has been investigated. The authors have concentrated on the requirement of small-scale EVAs for frequency regulation of electrical energy systems [109]. Accordingly, an analytic estimation of the probability distribution is accomplished in this study for modeling the procured power capacity (PPC). The optimal contract size is provided considering the previously obtained probability distribution of PPC by the proposed approximation method. The authors in [110] proposed stochastic optimal coordinating of charging and frequency control methods for EVAs, which achieves simultaneous optimization of EV charging and regulatory services. In this reference, the price uncertainty was modeled using Least Square Monte-Carlo (LSMC) and real-time market data. The authors have studied the implementation of EVAs as effective entities in frequency regulation in [111], where the appropriate charging-discharging of EV is used to provide the regulation service of the power system. In this study, a bidirectional frequency regulation scheme is considered instead of a unidirectional regulation framework, where the objectives are frequency regulation and maximizing the benefit of EVA. The variance minimization method is proposed in this research, which minimized SOC variance concerning the mean SOC average of the participating EVs. Similar research on the application of EVA in frequency regulation has been accomplished in [112], where stochastic analysis is accomplished for the relative value of energy capacity along with the battery size. This research investigated the effect of regulation in terms of SOC movement considering the symmetric and periodic characteristics of regulation. Optimal regulation allocation among EVs in an EVA system has been studied in [113] proposing synchronous and asynchronous distributed concepts. The proposed model has considered battery degradation cost considering operation in regulation service, the inefficiency of charging/discharging, and the gain/loss ratio. The main objective of this research is to optimize the cost of the difference between the requested regulation value and the sum of the contribution of EVs to the service. A centralized model is proposed for participation of EVA in the energy and regulation market in [114], proposing a real-time charging management framework for EVs. The proposed model is a hierarchical three-level control model, which allocates optimal charging set points to the EVs every few seconds. The basic process of charging allocation is the regulation signals received and updated energy bids and regulations offered by the EVA. A novel game theory is proposed in [115] for investigating the interactions between EVs and aggregators in the market, where the participation of EVs in the frequency regulation market has been studied. In this study, a smart pricing policy and a framework design for achieving optimal performance of frequency regulation in a distributed fashion are introduced. Nash equilibrium is applied in the V2G interaction games, which showed that a decentralized mechanism can achieve optimal performance just as in a centralized controlled system. The authors have proposed an optimal dispatching strategy for maximizing the profit of EVA and participating in the supplementary frequency regulation market [116]. In this study, a judge framework is proposed for determining the participating EVs of the



aggregator in frequency regulation, and a regulation power allocation strategy is introduced for allocating fair charge/discharge power of the participating EVs of the aggregator in frequency regulation. In [117], coordinated control of EVA is proposed for the participation of EVs in frequency regulation. Accordingly, a coordinated control strategy between EV-load frequency controller and conventional power generation units' load frequency controller is introduced to attain full advantages of EVs in such a regulation market. In addition, a robust stability criterion is presented in this study for estimating the asymptotically stable controller considering simultaneous inertia uncertainty and time-varying delays. A coordinated sectional droop charging control (CSDCC) framework is proposed in [118] for the participation of EVA in the frequency regulation market, which is applied to a microgrid with high penetration of renewable energy sources. In addition, a virtual inertia damping strategy is applied in the proposed control strategy for increasing the system inertia, which is implemented to avoid EV charging power vibration. In this study, the operation of EVs is considered only in charging mode without detrimental impacts on the battery life. In [119], an energy and reserve management model for a distribution network (DN) is proposed, in which an operation scheme for the EVA is implemented with the primary goal of lowering the DN's operating expenses. The EVs aggregator has three different states: load mode, energy production mode, and idle mode, where it will assist the DN as an energy storage system. The objective function is to reduce the upper grid's purchasing power expenses as well as the generator and EV aggregator's production costs, and the suggested model considered both the DG spinning reserve and the EVs aggregator.

#### 2.4. The Effect of EVAs on Network Characteristics

The effect analysis of EVAs on indexes of electric energy systems such as reliability, efficiency, losses, and stability shows improvements in such indexes. The effect of EVAs on network characteristics and indexes with a comprehensive overview is demonstrated in Figure 5. The role of EVAs in electrical energy markets, effect analysis of such agents in load profile of the electric distribution systems, and efficiency and security analysis of the penetration of EVs aggregator in day-ahead power market are defined as main contributions in the area of effect of EVAs in network characteristics. In addition, remarkable efforts have been carried out in the area of reliability improvement and valley filling of load profiles.



**Figure 5.** The effect of EVAs on network characteristics from different viewpoints.

With a discussion of the major contributions, limitations, research gaps, and prospects of the research works, Table 4 gives an overview of the impacts of EVAs on network characteristics.



**Table 4.** A summary of recently published papers around effects of EVAs on network characteristics.

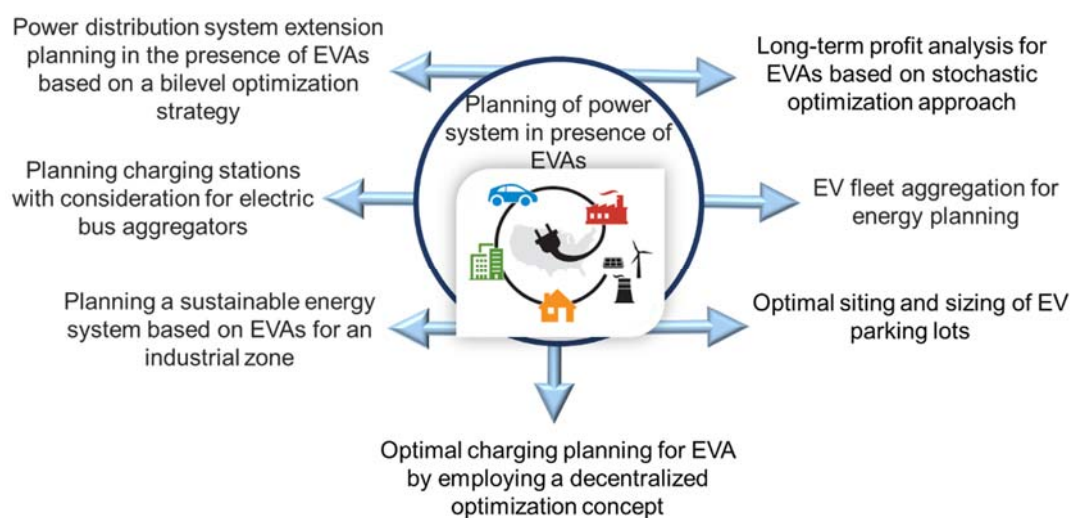
Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[120]	Power system load frequency control with EVA considering communication delay	Smart grids and communication characteristics, active power imbalance	Calculation of the time delay margin and transmission delay.	2022
[121]	V2G effects on electrical distribution systems with high EV penetration	Analysis of both unidirectional and bidirectional effects of V2G	Consideration of coalition of EVAs with renewables entities and financial incentives	2022
[122]	A hybrid risk-stochastic approach for assessing the impact of EVAs in transmission-constrained AC unit commitment	Injection of reactive power by EV charging stations to the system, demand response, uncertainties associated with wind energy sources and EV drivers' daily patterns	Real-time analysis of the role of EVs in energy systems	2021
[123]	Coordination of EVAs for distribution feeder peak shaving and valley filling	Bi-level programming, real-time operation model, EV drivers' comfort	Minimization of power losses considering power flows of the distribution system	2022
[124]	Load frequency stability analysis of time-delayed multi-area power systems with EVAs	Bessel-Legendre Inequality and Model Reconstruction Technique	Smart grids and communication characteristics	2020
[125]	Impact of non-systematic plug-in behavior on grid connected to EVAs	Agent-based model, large-scale EV case, flexibility analysis of power systems	Analysis of EV drivers' charging choices and EV usages	2021
[126]	Effects of EVAs on power grid operation risks and frequency	Frequency emergency control of electrical energy systems	Comfort levels of EV drivers when participating in V2G services	2020

The role of EVA in electrical energy markets has been studied in [127] by introducing a concept for the information characterization between aggregators, system operators, and costumers. In this study, the integration of EVs in the Iberian Market-MIBEL has been investigated and the formulation of various degrees of availability of the relevant information is proposed. Different strategies for adopting EVAs have been described in [128], where various tariffs proposed for EVAs depending on EV users' preferences have been investigated. In other words, different strategies that an aggregator can employ in user tariffs are analyzed in a case study for Quito, Ecuador. The authors have studied the application of EVAs in the load profile of the electric distribution systems, considering a case study of the transportation network of Zurich [129]. Accordingly, a tuning method is proposed in this study, which aims to valley filling and peak shaving by changing the utility function parameters in considering an external price signal. The effects of EV PLs on distribution system dependability are discussed in [130], where the distribution feeder's reliability indices are calculated utilizing a recently suggested unique storage capacity model of a PL that takes into consideration the load and component outage data of the feeder. The average interruption duration, average interruption frequency, and energy not served are all used in this study as reliability indexes. The authors have concentrated on the design of a typical day-ahead power market for the integration of EVA in the power system in [131], which takes advantage of increasing the efficiency and security of the system and decreasing the environmental effects. The model investigates the relationship between the coordination of the charging schedule of EVs and the capability of the system in admitting penetration of such vehicles. The proposed model permits V2G services in

the adapted market design considering service limitations on the provision. The authors have studied the role of EVA in improving the reliability of the power system by supplying the spinning reserve of the system [132]. The proposed model is effective in obtaining the optimal charging schedule of the vehicles while improving the reliability and cost of the system. An agent-based model is proposed for modeling the aggregator participation in spinning reserve, and a dynamic game theory is adopted for deciding on the market players offers in electricity market. In other words, the model investigates the compromise between the cost of spinning reserve supply and the cost of system risk. In [133], the distributed optimization of EVA has been studied considering two relevant objectives, which include valley filling and minimum charging cost. The proposed framework, which consists of local and global objectives, is based on the alternating direction method of multipliers (ADMM) approach. The authors have evaluated the proposed model for 1 million EVs and 100,000 EVs for the valley filling problem and both valley filling and charging cost minimization, respectively. The authors have studied the impacts of market regulations on the behavior of the EV owners and EVA in [134], where both the regulator and aggregator points of view have been considered. In this study, an offering/bidding strategy is modeled by applying a hybrid method based on multi-agents and a dynamic game. In addition, the optimal probabilistic operation of EVs is studied considering uncertainties associated with driving patterns and electricity market prices taking technical and contractual constraints into account. A stochastic model is proposed in [135] for evaluating the effects of EVA on distribution systems. In this reference, MCS is applied for investigating the stochastic nature of EVs load, including stochastic spatial and temporal characteristics. The investigations show that suitable optimization and the control scheme of EVs is effective in eliminating the negative effects of EV loads on voltage levels, phase unbalances, and system losses. In [136], the aggregated load imposed on the electricity distribution network by battery health-conscious charging of EVs is estimated. The daily energy cost of EVs and degradation cost are considered a multi-objective optimization problem for obtaining optimal charging magnitudes and time of charging. Then, aggregated EVs power load demand and the related peak load is investigated using results obtained for aggregated EVs charge patterns optimized. Short-term allocation of reactive power and definition of reactive power supply function (RPSF) for aggregated EVs are studied in [137], which allows the system operator to engage EVs in the reactive dispatch of the network. Accordingly, a real-time method is proposed in this study for calculating the reactive power supply function of the EVs after estimating the optimal set points of EVs. The proposed model enables EVs for supplying reactive power service with low marginal cost during on-peak periods. In [138], for enhancing the reliability of radial distribution systems using the particle swarm optimization algorithm, DR programming and smart charging/discharging of EVs are examined. Due to the good benefits of both DR and EVs in dealing with emerging global concerns such as the decline of fossil fuel reserves, urban air pollution, and greenhouse gas emissions, this analysis was completed. Additionally, the prioritization of DR and EVs is described as increasing distribution network dependability and assessing distribution network characteristics.

### 2.5. Planning of the Power System in the Presence of EVAs

The power system integrated with EVAs makes use of car batteries to help the electrical energy network; however, the planning of the power system should be done taking into account challenges of the system operator, such as reliability challenges, congestion, and loss increase. Figure 6 shows different viewpoints on the planning of power systems in the presence of EVAs. Welfare maximization of EVs aggregator systems in long-term conditions, aggregation of the battery modeling for energy planning, and optimal siting and sizing of vehicle parking are the primary contributions to power system planning in the presence of EVAs. Also, efficiency and reliability investigations, as well as economic analysis, are studied as planning topics for such systems.



**Figure 6.** The planning of EVAs in different viewpoints.

Table 5 provides an overview of the planning of EVAs, along with a discussion of the major contributions, constraints, research gaps, and future directions of the research works.

**Table 5.** A summary of recently published papers around planning of EVAs.

Ref.	Main Contributions	Considerations	Research Gaps/Future Directions	Published Year
[139]	An economical method for integrated community microgrid with EVAs	Microgrid with 100-house community, solar photovoltaic system	Consideration of forecasting uncertainties associated with EV drivers' behavior and renewable power	2019
[140]	Power distribution systems' robust coordinated operational planning with EVAs	Forecasting uncertainties, V2G, Renewable energy sources	Consideration of role of the power loss and smart grids communications	2020
[141]	Planning a sustainable energy system that uses EVs as energy storage for an industrial zone	Considering different scenarios including uncoordinated, unidirectional and bidirectional charging, stochastic optimization	Sensitivity analysis of penetration of renewable energy sources	2020
[142]	Model for planning charging stations with consideration for electric bus aggregators	Electric buses, capital and maintenance costs.	Electric buses effects on other power grids with distributed generators	2022
[143]	Optimal bilevel operation-planning framework for distributed generation hosting capacity with EVAs	Application of hybrid conditional-value-at-risk (CVaR) and stochastic programming	Game-theoretic framework for electricity exchange between EVA and grid operators	2021
[144]	Planning for distribution growth in the presence of EVAs based on a bilevel optimization strategy	Consideration of investment and operational constraints, multi-stage stochastic optimization	AC power flow model, dealing with computational complexity	2021

A novel optimization problem for the optimal allocation problem of EV parking lots and the optimal scheduling of EVs in a smart distribution network are investigated in [18]. The proposed problem considers a variety of elements, including technological and economic concerns, to arrive at a feasible solution, where minimizing network losses and feeder voltage drop, as well as meeting all network demand, are all taken into account

as technical concerns. The authors in [145] provided a new solution methodology for evaluating the optimal allocations and sizes of parking lots in radial distribution networks that incorporates a current metaheuristic approach of competition over resources. The key goal is to improve network resilience while keeping costs low, where enhancing reliability, improving power loss cost, and decreasing investment costs are considered. In [146], a welfare-maximizing regulation allocation (WMRA) approach was proposed to explore the coordination of numerous EVs to execute EVA regulatory services. The proposed algorithm's major goal is to maximize the EVA system's long-term societal welfare while taking into account the expense of EV battery degradation over time. The proposed WMRA algorithm, which is based on a broad Lyapunov optimization model, operates in real-time and does not require any information on the system statistics. The authors in [147] proposed a flexible structure for aggregating batteries of the EVs and performing aggregation modeling for energy planning. The suggested model also uses input time distributions such as average SoC at destination and the number of incoming and departing vehicles. To acquire charging power input and distributed charging management, dynamic programming is used. The authors in [148] investigated the ideal siting and sizing of aggregator vehicle parks to achieve the lowest power loss and voltage variations. As a result, particle swarm optimization (PSO) is used to determine the best park location and size, as well as to investigate the best power flow after the car park is installed. This model can be used to investigate how to increase the stability and dependability of the power network for park siting and sizing. The authors have proposed an idea for effective usage of capacity and energy of the parked EVs in [149], considering the EVs parking average of 92% of the day. Accordingly, an aggregating control scheme is proposed for controlling bids in the German market using the MCS model. In other words, the main objective of this paper is to investigate the participation of EVs in providing control power in terms of efficiency, reliability, and economic aspects. An optimal charging planning for EVA has been studied in [150] by employing a decentralized optimization concept. The proposed decentralized method computes the capability of each EV in their charging tendency in a distributed way, which results in determining the charging tendency of a small number of EVs by an aggregator. The long-term goal of the aggregator for improving market share and acquiring optimal rates of the aggregator has been explored in [151], where the long-term goal of the aggregator for enhancing market share and obtaining optimal tariffs of the aggregator has been studied. In this study, oligopoly energy and reserve markets have been modeled by employing a bi-level formulation using a multi-agent system and dynamic game theory. Accordingly, the optimal self-scheduling of EVA and best bidding/offering strategies are obtained.

### 3. Research Gaps and Future Research Directions

Although various research studies have been published around EVAs in electric distribution networks, several challenges still exist around modeling EVAs. The following items are listed as important challenges and issues as future directions for research around EVAs:

- Improvement of the market bidding strategies considering a comprehensive uncertainty-handling concept, which models all the uncertainties associated with EV drivers' behavior as the arrival/departure time of the EV driver to/from the charging station, the daily trip pattern, and SOC of the battery of the EV, renewable energy sources, load of the system, and power market price. For example, hybrid stochastic programming and robust optimization/information gap decision theory methods can be used for modeling the uncertainties associated with charging and regulation prices, as well as EV drivers' behavior in optimal operation, control, and bidding processes of the EVAs. In such an area, the investigation of a dynamic model of large-scale EVAs, considering the stochastic nature of EVs and network of parking stations of EVs (i.e., a network of EV charging stations with smart management and communications) is essential.
- Implementation of decomposition techniques methods for improving the optimization and computational process of the problems associated with EVAs in energy systems.

The employment of decomposition methods is beneficial to parallelizing the solving techniques for multi-cluster high-performance computing when dealing with EVAs integration to energy markets and electric utilities. Such methods will be helpful in studying the coordination of EVAs in non-spinning reserve and energy markets as well as storage systems such as fly-wheels or other battery-based energy storage systems in the energy market services. Also, coordinated operation of MGs containing EVAs and demand response resources for providing active and reactive power to the grid can be studied by such models.

- When assessing the role of EVs as load/storage in modeling the operation of the energy system, forecasting the behavior of EV drivers is crucial. For this reason, increment of the precision and evaluation metrics of the prediction models for EVs considering the forecasting uncertainty is crucial. For energy grids to operate reliably and optimally, researchers should create high-performance load modeling and prediction models of EV energy demand. In such an area, application of clustering models for classification of EV drivers' behavior to different clusters is beneficial. Also, the integration of EVAs to energy markets and clusters of microgrids with high penetration of renewable energy sources and large popularity of EVs can be modeled by applying appropriate machine learning and deep learning models.
- Investigating insights into the battery degradation problem in real-time dispatch of the EVAs in energy markets, and implementation of complementarity modeling to evaluate price equilibria between interacting agents at the retail level for eliminating the supposition of centralized direct load control are other important topics to be focused on. A crucial part of EVs is the battery, for which the degradation should be considered when modeling the vehicle and if the battery pack will be used in V2G modes. Given the economic and environmental factors, multi-objective optimizations should consider the trade-off between several objectives, including energy prices, pollutant gas emissions, battery degradation, and compensating vehicle drivers for V2G services. In this situation, it is important to consider each aim fairly while comparing them, which can be done by applying a game-theoretic analysis.
- Future directions may also focus on competition of EVAs with each other and with other entities such as DR aggregators, network-constrained optimal operation of energy hubs/residential communities/electric utilities and EVAs, consideration of coalition of EVAs with renewables entities and financial incentives, and study on comfort levels of EV drivers when participating in V2G services.

#### 4. Conclusions

The high penetration of EVs in electric distribution networks and future smart grids play effective roles in network indexes and environmental aspects, which is more sensible while aggregated by an agent. Accordingly, several remarkable efforts have been performed around EVAs, considering the challenges of such issues in power markets, electrical energy systems, and operation and planning issues. This paper aimed to provide a comprehensive review and outlook on EVAs and electric energy networks. For each research study published around EVAs, most of the contributions of each research study and novelties in modeling the EVA are investigated and reported upon. Moreover, the main considerations of research around EVAs studied by different researchers are discussed. Additionally, future trends around EVAs and their application in energy systems are introduced, which can be considered the subject of research studies in such areas in the future. This paper, which provided a comprehensive review and outlook on the application of EVAs in energy systems, can largely help the researchers around EVAs.

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