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A Holistic Review on E-Mobility Service Optimization: Challenges, Recent Progress and Future Directions

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***Abstract*—In recent years, countries around the world have attached great attention to the development of transportation electrification. As an alternative to achieve carbon neutrality, Electric Vehicles (EVs) are deemed as the goal of vehicle transformation to achieve zero carbon emissions. However, the challenges of EV energy supplementation has not been adequately investigated, causing the concerns on range anxiety, inconvenience of perceive charging service etc. By identifying stakeholders and investigating various services under the umbrella of E-mobility services, this paper firstly introduces the concept, population and challenges of EVs as the key enabler of Electro-Mobility (E-Mobility), and then summarizes recent E-Mobility services with holistic insight. Then, overviews of plug-in charging, battery swapping, vehicle to vehicle charging, mobile and wireless charging are introduced, including the objectives, risks and their service optimization categories. Further to literature review, concern on identifying the gap between academia and industry application is also provided to help coach the technology transformation. From our review, it is observed that flexible and emerging service modes beyond plug-in charging has been receiving great attention from both academia and industry. Therefore, several recent market efforts have been showcased, by following the summarization of mainstream optimization methods been applied for E-Mobility services. Finally, this paper is concluded with several future direction highlights including integration of multi-energy source, concern on cyber security, application of Artificial Intelligence (AI) and promotion of global policy to guide with wide communities.**

***Index Terms*—E-Mobility, Transportation Electrification, Electric Vehicle, Charging Infrastructures, Battery Swapping, Service Optimization.**

I. INTRODUCTION

Electro Mobility (or E-Mobility) represents the concept of using electric powertrain technologies, in-vehicle information,

Table I. List of Commonly Used Abbreviations

E-Mobility	Electro-Mobility
EV	Electric Vehicle
ICE	Internal Combustion Engine
CS	Charging Station
BSS	Battery Swapping Station
P2P	Peer-to-Peer
V2V	Vehicle to Vehicle
MCS	Mobile Charging Stations
ICT	Information and Communications Technology
RES	Renewable Energy Sources
AC	Alternating Current
DC	Direct Current
V2X	Vehicle-to-Everything
MEC	Mobile Edge Computing
AI	Artificial Intelligence
MILP	Mixed Integer Linear Programming
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
GC	Global Controller
QoE	Quality of Experience
SOC	State of Charge
PV	Photovoltaic
BES	Battery Energy Storage
G2V	Grid to Vehicle
V2G	Vehicle to Grid
ET	Electric Taxis
CC-CV	Constant-Current/Constant-Voltage
B2G	Battery to Grid
BSCS	Battery Swapping and Charging Station
MDP	Markov Decision Process
BCS	Battery Charging Station
PSS	Power Storage Station
ILP	Integer Linear Programming
MCT	Mobile Charging Truck
FCS	Fixed location Charging Station
PCS	Portable Charging Station
DWC	Dynamic Wireless Charging
SWC	Static Wireless Charging

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communication technologies and connected infrastructures, to enable the electrification of vehicles. It allows vehicles to alleviate CO2-emitting fossil fuels towards energy supplied from electrical power sources which are, in turn, charged through the electricity grid. Here, Electric Vehicles (EVs) (driven by motors and powered by electric energy, thus breaking away from dependence oil) will become an enabler for the integration of future transportation and energy systems [1]. Countries around the world have begun to deploy the EV market as a means of transportation in the future, meanwhile released a timetable for banning the sale of traditional energy vehicles.

Canada and UK have announced, and adopted policies to promote full transition from internal combustion engines to EVs by 2040 [2]. Besides, China has started to reduce investments in Internal Combustion Engine (ICE) production plants from 2019, promotion the way for EV sales. In addition, about 10 US states have mandatory zero-emission vehicles, and California will have 5 million EVs on the road by 2030 [3]. In 2020, Europe established the EU-wide EV procurement mechanism, which is expected to reach 20 billion euros within two years. Europe also planed to invest up to 60 billion euros in the powertrain direction of EVs, trying to double the investment in charging systems for construction to 2 million public charging piles by 2025.

A. Popularity of E-Mobility

The consumers' preference for EVs is affected by many factors. Identifying the factors influencing the promotion of EVs will help the government to formulate, or adjust EV incentive policies in a targeted manner. Therefore, in addition to evaluating the effects of existing policies, there are studies on the factors affecting the promotion of EVs. The proportion of renewable energy in electricity production, the number of charging stations, consumers' education level and population density will have an impact on the demand for EVs [4]. Wang et al. [5] found that the density of charging piles, fuel prices and road priority, has a positive impact on the market share of EVs. Similarly, Figenbaum et al. [6] analysed that the increase in EVs models, technological progress, and price reduction will stimulate EVs sales.

1) Policy Incentives: In order to promote EVs market and technologies evolution, countries around the world have established a wide range of multilateral cooperation mechanisms. The size of the EV market is growing rapidly, according to a report, the global sales of EVs reached 4.8 million in 2021, with China being the largest market, accounting for 44% of the global EV sales. Europe and the United States accounted for 25% and 18% of the global EV sales, respectively [7]. In terms of charging infrastructure, according to data from the International Energy Agency [8], as of the end of 2021, there were more than 1.5 million public charging stations worldwide, with China having the most charging stations, accounting for 40% of the total. Europe and the United States accounted for 24% and 18% of the world's total charging stations, respectively. These data indicate that the EV market is growing rapidly, and the construction of charging infrastructure is also accelerating.

2) Industry Development: The following will introduce the main types of industrial developments related to EVs.

The Rise of Renewable Energy Sources (RESs): The large-scale application of EVs must be decoupled from dependence on fossil energy. The vehicle in the future will be an unit in the energy system with Internet, as an important carrier for storing and consuming renewable energy. Many countries consider the development of renewable energy as an importance in their energy strategies, have formulated clear development goals and policies, laws and regulations. As for car manufacturers and charging companies, they both realize the importance of adopting RESs to power EVs. Here, EVgo is the largest US charging service supplier, and provides 100% RESs electricity [9].

Battery and Charging Power: The power battery is the main energy system of EV, as the major obstacle hindering the development of EV [10]. With the growth of EV sales, the installed capacity of power batteries has been under continuous growth. The charging applications of EV mainly includes plug-in charging and battery swapping. The charging modes include the common Alternating Current (AC) slow charging mode of household piles, and the Direct Current (DC) fast charging mode of public piles. The fast charging mode is in the process of rapid upgrade and evolution, where the charging power is increasing from 200kW to 400kW and the charging time is shortening from 30 minutes to 15 minutes [11]. Alternatively, the battery swap mode is to replace the battery of EV at Battery Swapping Station (BSS), with NIO as the typical representative. Besides, the power of Vehicle-to-Vehicle (V2V) charging is normally 20kW, for example, actual V2V charging experiments have been conducted between BYD EVs and Tesla EVs [12].

Structure of EVs: In the era of fuel vehicles, the competition of car manufacturers is highly differentiated. Even if the technical direction is the same, major car manufacturers still have their unique technical barriers. However, this kind of differentiation for EVs market is extremely difficult to maintain. First of all, the structure of entire electric drive is very simple, with the three-electrical structure represents cores of electric drive. Regardless of the battery, motor or electronic control, the degree of standardization of components is very high. Under the premise of standardization and components, manufacturers can easily dominate the market.

B. Challenges of EVs Adoption

As shown in Fig. 1, although with policy and industry development in promoting E-Mobility, the following challenges are still of necessity to overcome.

1) Concern on Range Anxiety: The range anxiety refers to the mental distress or anxiety caused by worrying about a sudden loss of power while driving an EV [13]. Due to characteristics of batteries, the cruising range of EVs is obviously reduced in winter, while the use of air conditioners obviously affects the cruising range. Here, Table II illustrates the driving range of typical EVs in the market.

2) Shortage of Infrastructures: The concern on range anxiety is also partially caused by the limited construction of

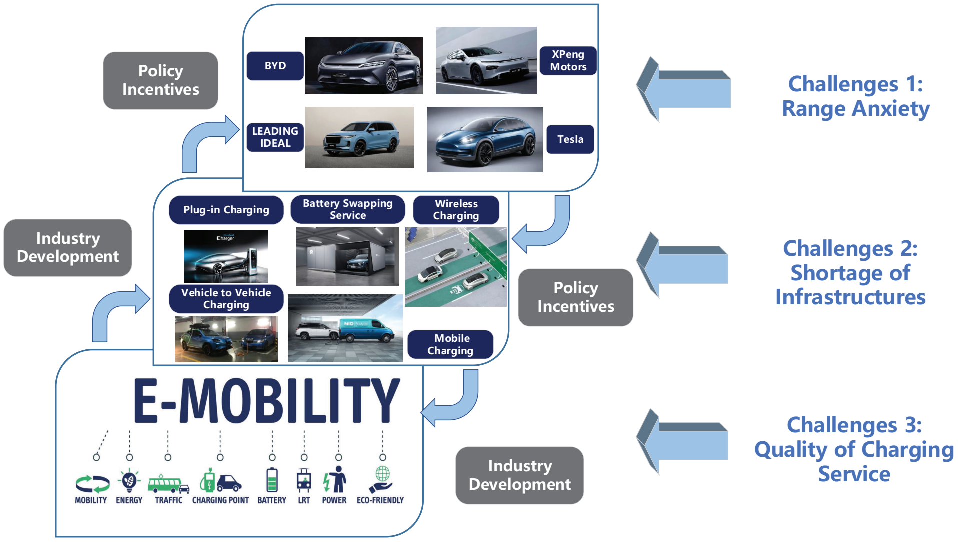


Fig. 1. Overview of Developments and Challenges in E-Mobility

Table II. Vehicle Mileage

Brand	Model	WLTP Range	EPA Range
Tesla	Model S	373miles	348miles
Tesla	Model 3	374miles	315miles
Tesla	Model X Plaid	337miles	311miles
Tesla	Model Y	331miles	303miles
Lucid	Air	496miles	520miles
NIO	ES8	311miles	NA
NIO	ES6 (510KM)	317miles	NA
BYD	Tang	249miles	NA
Lexus	UX 300e	196miles	180miles
Ford	Mustang Mach-E	273miles	277miles
BMW	iX3	286miles	279miles
BMW	i4	366miles	301miles

energy supplement infrastructures, compared with the large number of EVs. Normally, this depends on the following reasons:

The Difficulty of Spatial Deployment: According to MIT Technology Review reports [14], the U.S. sold 400000 EVs in 2021, but has only 48000 Charging Stations (CSs) deployed over the whole country. Regardless of plug-in charging, battery swapping service or other energy supplements methods, the extra land space is necessary for construction of infrastructures for energy supplements. However, since different charging protocols between EVs can lead to failure of V2V charging, there is the shortage of infrastructures that V2V charging requires a DC-DC converter that can adapt to multiple charging protocols [15].

The Difficulty of Charging Compatibility: Heterogeneous EVs are with incompatibility of batteries, e.g., in US, the battery capacity of the Nissan Leaf EV is 24kwh, while the Ford Focus EV is 23kWh and BYD e6 EV is 57kWh. Besides, the current power of wireless charging for EVs varies depending on the technology used, although its charging power remains mostly low compared to plug-in charging.

The Difficulty of Grids Capacity: The charging behavior of EVs brings a great challenge to the stability and load of power grid. Considering the limited load capacity of power system, the deployment of charging infrastructure should be carefully planned. Besides, the service ability of grids needs constant improvement, to satisfy the rapid increment of EV charging requirements.

3) Quality of Charging Service: At present, the charging time of EVs is relatively long, while the owners need to spend more time to supplement the energy than fuel vehicles. With the continuous improvement of the driving range of EVs, there is an urgent need to greatly improve the charging efficiency. Firstly, large-scale urban parking space resources are tight, it is impossible to realize the exclusive use of charging parking spaces. Secondly, additional consumption (such as parking fees, lounge consumption, etc.) generated during the charging of EVs, also increases the service cost. Thirdly, considering the real-time requirement of energy supplement, finding an approximate station (e.g., CS or BSS) for recharging batteries is the main concern for EV drivers.

C. *Intention of Our Review*

Suffering from challenges of EV energy supplement, researchers have conducted several studies to optimize service operations. Literature [16] investigated EV charging scheduling, and classified review papers into unidirectional versus bidirectional charging manners with CS. Upon the classification, two branches are further distinguished according to whether the scheduling is performed under centralized or distributed framework. Further to [16], clustering and forecasting methods based on artificial intelligence are utilized for classifying literature on EV charging control in [17]. In addition, the review in [18] pays more attention to energy-efficient routing and charge optimization. Whereas, the concern from service operators (stakeholders operating charging infrastructures) and users (people experience the charging service) sides is still absent.

Although the optimization related to EV charging has attracted increasing attention, the deployment and management of charging infrastructures is still the main concern [19]. As the alternative to plug-in charging, the necessity, opportunities and challenges of battery swapping service have been discussed [20, 21]. Considering the role of BSS as a grid scale energy storage, the relation of BSS, EVs and power grid has been covered in [22]. The research about siting, sizing and optimal scheduling for BSSs and routing of EVs have been reviewed in [23], while literature [24] further classified review paper into the angle of single BSS, multiple BSSs, integration between BSS and CS.

In terms of energy supplement infrastructures, plug-in charging and battery swapping still share the common service cycle (mainly from angle of service operator) to charge batteries either directly at EVs or indirectly removed from EVs. The difference in these two applications lies in how to serve users, either through the plug-in charger or automated swapping platform. In addition, the V2V energy supplement manner benefits more from the preference from pairwise users agreed under the Peer-to-Peer (P2P) business model, with extension of running with mobile suppliers or wireless converters. The work in [25] reviewed the literature with focus on operation and dispatch of Mobile Charging Stations (MCSs), including MCS scheduling and cost reduction, but fail to follow the emerging in-motion EV charging case. Literature [26] analysed the hardware level technology of wireless charging. Given concerns about the safety of wireless charging, it also summarized the literature on safety and sustainability. Literature [27], on the other hand, analysed the economic benefits of different applications for static and dynamic wireless charging. However, above literature on wireless charging rarely considers the optimization of the quality of wireless charging services.

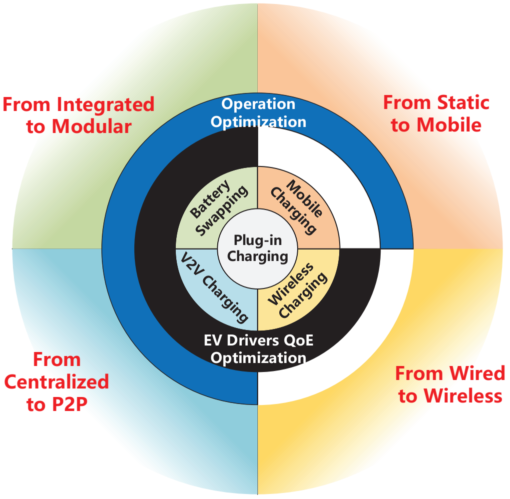


Fig. 2. Relationship Across E-Mobility Services

In our review paper, we summarize existing E-Mobility services in literature as a holistic ecosystem, shown in Fig. 2. Specifically, our review paper positions the plug-in charging service as the ground to gear the development of V2V charging, mobile charging and wireless charging services respectively. Clearly, these are evolved from the angles of *charging from centralized to P2P manner, from static to mobile and wireless manners*. It is highlighted that the battery swapping service is linkable to plug-in charging service, as it still relies on powertrain technologies to supple depleted batteries. However due to decoupling battery charging from EV, such type of service is deemed with the angle of *charging from integrated to modular manner*, potentially via mobile and wireless charging manners. Clearly, it is highlighted that our review paper has unlocked the link across a number of E-Mobility services. While with such evolution, there is necessity to further reshape the technologies of service optimization under the umbrella E-Mobility.

D. *Contributions of Our Review*

Following the intention, Table III summarizes the contributions of recent review papers versus our review. In summary, above literature positions technology review for service optimization per single service type, but fails to understand technology evolution that been applied from the angle of service operators and users. Following the worldwide ambition in achieving the low carbon transportation, emerging service such as P2P charging by alleviating the influence of service operators in line with mobile and wireless supplement manners are also promising. Based on above, the main contributions of our review paper are as follows:

- As an advance of vision, this paper lies in E-Mobility service optimization, covering already commercialized plug-in charging, battery swap application services, and also recent innovation services of P2P energy transfer between EVs and other portable stakeholders. Beyond literature, we summarize above services under a holistic view, by unlocking the internal relationship across them with meaningful technology evolution trend.
- Following our holistic view, this review paper further decouples the optimization technologies from angle of service operator and user. Technology features and optimization methods under each application service, are classified and reviewed comprehensively.
- An in-depth investigation of optimization methods applied in literature is given, with logical relationship unlocked to help with understanding. Along with that, this review paper attempts to identify the gap between academia and industrial communities, further showcases the discussion on technology to market, with aim to promote technology transformation in the field.

As shown in Fig. 3, our review paper is organized as follows: Section I introduces popularity perspective, challenges of E-Mobility with the summary of literature in the field, followed by the intention and contributions of our review. Section II, Section III, Section IV introduce the decision framework, risks and optimization objective and categories for plug-in charging, battery swapping and V2V charging services. It is highlighted that the optimization methods been applied in literature, are categorized into the angles for operators and

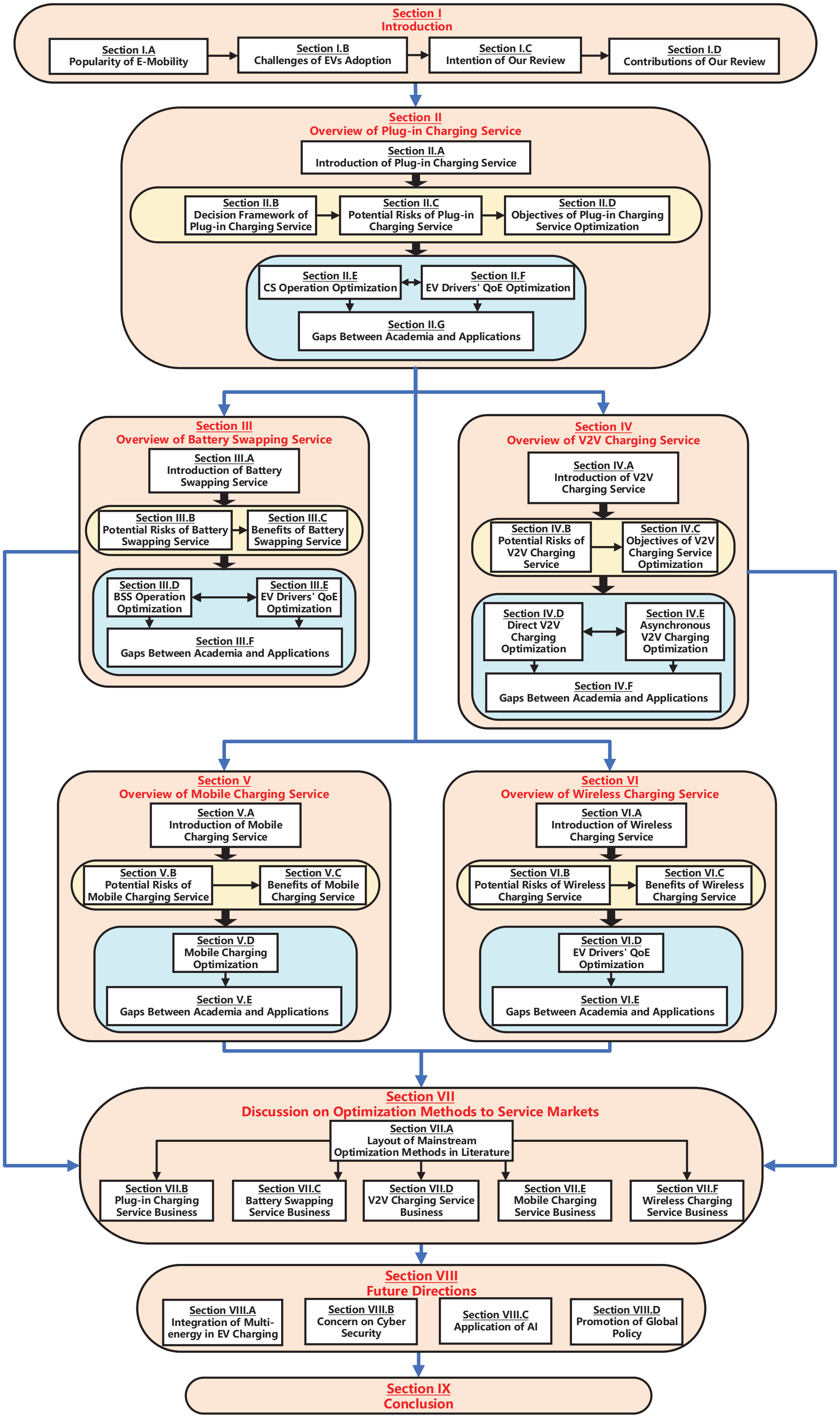


Fig. 3. The Organization of This Paper

Table III. Summary of Literature and Our Contributions

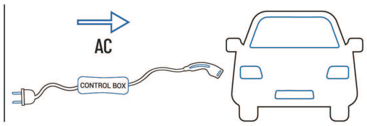
Application Service	Literatures	Angle of Review
Plug-in Charging	Literature [18], 2014	Energy-efficient EV routing, Congestion management, Integration of EVs into Smart Grid.
	Literature [16], 2015	Control of directional power flow, Centralized versus decentralized charging control manner, Interacting with power grid.
	Literature [17], 2019	Experimental data sources, EV charging methods, Solver software.
	Literature [19], 2020	EV aggregator deployment, G2V and V2G optimization.
Battery Swapping	Literature [24], 2021	Planning of BSSs and BCSs, Battery swapping service scenarios.
	Literature [22], 2021	Battery swapping service optimization from operators side.
	Literature [23], 2022	BSS siting and sizing, Batteries charging scheduling, Cost-benefit analysis of EV service behavior.
Mobile Charging	Literature [25], 2021	Practical applications of mobile charging.
Wireless Charging	Literature [26], 2021	Safety and sustainability of wireless charging, Economic and social impact analysis.
	Literature [27], 2018	Static and dynamic wireless charging applications, Investigation of electromagnetic field shielding methods.
Plug-in Charging, Battery Swapping V2V Charging, Mobile Charging Wireless Charging	Our Review Paper	Holistic insight into E-Mobility services. Coverage of emerging E-Mobility services. Service optimization category from operators and users sides. Discussion on mainstream technologies for E-Mobility services optimization, and technologies to market. Following up-to-date literature by 2022.

EV drivers. Besides, Sections V and VI focus on innovation of mobile and wireless charging that can be applied together with those already commercialized services. Finally, with investigation in Section VII, this review paper is concluded with several future directions in Section VIII.

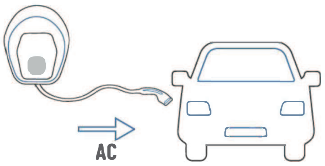
II. Overview of Plug-in Charging Service

A. *Introduction of Plug-in Charging Service*

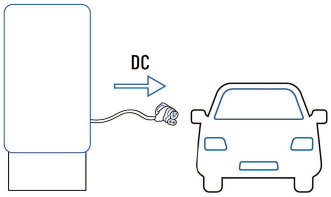
As the most prevalent energy supplement method, the plug-in charging service has attracted increasing attention due to the property of convenience, economy, etc. Therefore, the research on EV charging under plug-in mode is of great significance considering the large scale of EVs. Fig. 4 presents three typical plug-in charging modes. In Fig. 4(a), a control box is placed on the charging cable to ensure the charging safety between the connection of electrical network and the EV in charge [28]. Considering the charging performance and safety, the portable charger integrated the control box is widely applied with both domestic and industrial sockets. Fig. 4(b) is designed for wallboxes, commercial charging points and all automatic charging systems in AC. With the advanced equipment, EVs can be charged with 32A and 250V in single-phase, while up to 32A and 480V in three-phase. Fig. 4(c) is the only charging mode that provides DC. Before the current passes through the charging cable towards EVs, an external current converter is necessary to transform it from AC into DC.



(a) Mode 1



(b) Mode 2



(c) Mode 3

Fig. 4. Plug-in Charging Modes

As for optimization on plug-in charging service, the following methods are most often adopted:

Mathematical Optimization: Typical methods include linear programming, Mixed-Integer Linear Programming (MILP), quadratic programming and robust optimization. Above optimization problems can be solved with commercial or professional software where CPLEX [29], LINGO [30], GLPK [31] and IPsolve [32] are the most common tools.

Operational Research: Typical methods include queuing theory, game theory. Considering the computational complexity with large density of EVs and CSs in practical case, above solver tools of mathematical optimization are not always applicable. With regard to the characteristic of large-scale optimization problem, solutions related to operation research are thus applied.

Meta-heuristic Algorithms: Typical methods include Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and evolutionary algorithms. Since traditional optimization algorithms are hard to deal with large-scale mobile scenarios, meta-heuristic algorithms have thus been applied to obtain an approximate optimal solution.

B. Decision Framework of Plug-in Charging Service

It has been proven that reasonable control manners can improve the optimization performance given demands constraints [33]. The benefit of cooperative control between EVs and the service operator has also been depicted in literature [34]. Here, there are two main types of decision-making frameworks as follows.

Centralized Control: The centralized control framework is the most common under plug-in charging service. The centralized system aggregates the global information, including charging demand of all EVs and service capability of all CSs. Based on comprehensive information, the centralized system can thus obtain the optimal solution. Besides, a central entity that aggregates and deals with global information is necessary to implement centralized decision-making. The entity is usually called the Global Controller (GC). Compared to the decentralized control framework, the centralized control framework is efficiently executed in practical application, due to lower communication cost and time delays.

Decentralized Control: As discussed above, the centralized control framework can obtain the optimal solution in global manner. However, it also faces challenges such as robustness and privacy issue. The decentralized control framework has been proposed as an essential supplement to the centralized framework. Its advantage is that it can share information only with local infrastructure rather than aggregating all data at a central entity, instead it only requires a minimal computational resource on the local side. It should also be noticed that the decentralized control framework is hard to obtain the globally optimality, without complete knowledge of global view.

C. Potential Risks of Plug-in Charging Service

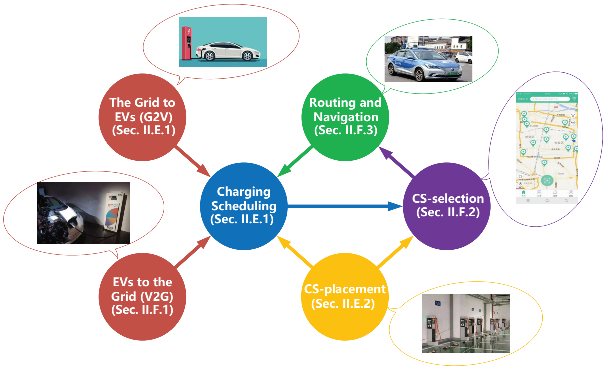


Fig. 5. Relation of Service Optimization under Plug-in Charging Service

Here, we briefly summarize the potential risks of above control frameworks.

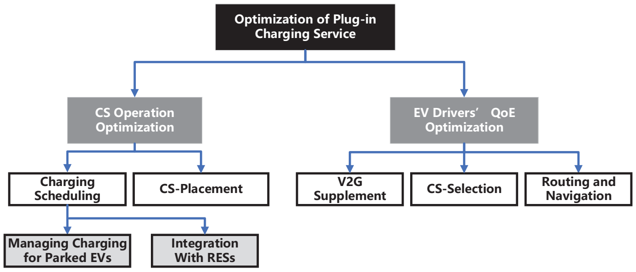
Infrastructure Construction: To support communication among entities, primary infrastructures over networks are necessary. Therefore, the construction of communication facilities is the fundament of EV charging.

Privacy Issues: Regardless of centralized or decentralized frameworks, EVs send information about their IDs, locations and destinations to a third party. The private information should be protected and prevented for commercial and security purposes.

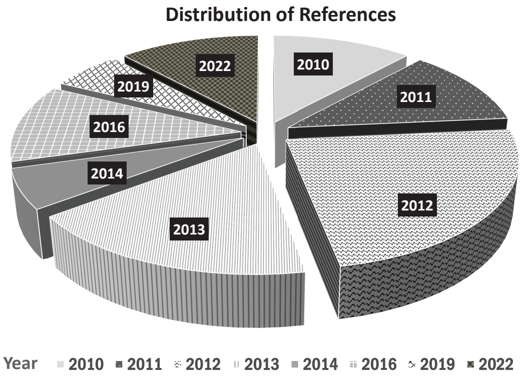
Coordinated Management: Different service stakeholders tend to make decisions that benefit their interests. A coordinated management scheme that balances the demand of various entries is thus essential for long-term operation.

In above paragraphs, we have introduced primary concerns and basic methods for the plug-in charging service. Based on these preliminaries, we present typical application scenarios under plug-in charging service as follows. The relation of each application under plug-in charging service is depicted in Fig. 5.

D. Objectives of Plug-in Charging Service Optimization



(a) Optimization Category under Plug-in Charging Service



(b) Literature under Plug-in Charging Service Optimization

Fig. 6. Overview of Plug-in Charging Service Optimization

The objective of EV charging determines the optimization problem formulation and decision behavior for different service stakeholders. Here, we further analyze the objective from the perspective of multi-party stakeholders in charging service.

From the power grid's perspective, it mainly concerns peak load shifting, voltage fluctuations and power system load variance, to maintain the stability of electricity service network. The renewable energy such as wind, hydro, solar, and geothermal is also important energy sources that can be fully utilized. Upon that, the power grid can alleviate dependence on fossil fuels, and reduce power generation cost.

From EV drivers' perspective, the Quality of Experience (QoE), namely the service waiting time, is the primary concern. Besides, charging cost is another crucial factor. The cost usually consists of two aspects: the battery degradation cost caused by charging and the charging expense paid to CSs.

From CSs' perspective, the operation profit is the determinant for long-term running. To maximize the profit, the CS operator should improve the charging revenue from EVs, and reduce the expenditure on purchasing electricity. Additionally, the departure deadline is normally taken into account, so as to address the user tolerance on charging service.

Here, Fig. 6(a) shows the optimization category under plug-in charging application, while Fig. 6(b) shows the literature year on plug-in charging service optimization based on our review. It is observed that although the service optimization under plug-in charging was widely studied, there are still ongoing efforts in recent three years. In the following review of this section, we decouple our understanding into **CS Operation Optimization** for service operator's angle and **EV Drivers' QoE Optimization** for client's angle.

E. CS Operation Optimization

Under the following scenarios, the optimal decision is mainly concerned from the perspective of CSs. With a focus on these scenarios, the operation optimization can be achieved at CSs from construction to charging scheduling. Therefore, optimization objectives from the perspective of CSs are eventually realized based on these analysis.

1) Charging Scheduling: The optimization problem of charging scheduling is usually formulated as allocating each time slot for optimal charging/discharging. Table IV compares related works in charging scheduling under plug-in charging service.

Table IV. Summary of Charging Scheduling under Plug-in Charging Service

Year	Ref.	Methods & Techniques	Objectives
2010	[35]	Dynamic programming	Revenue maximization; Frequency regulation
2010	[36]	K-nearest neighbor	Reduce electricity cost
2013	[37]	Optimal control process	Peak-load shifting
2012	[38]	Convex relaxation optimization	Maximize user convenience; Maintain power grid stability
2022	[39]	Look-ahead dispatch	Maximize CS profits
2019	[40]	Four-stage optimization and control	Reduce operation cost

[Managing Charging Behavior for Parked EVs]

EVs are usually parked at a building and connected to the power grid with a wired connection. The problem is defined as when/whether to charge, here EVs are regarded as static consumers without considering the property of mobility. EVs set the target State of Charge (SOC) and the departure time to the CS operator. Based on demand of serviced EVs, the CS operator determines optimal charging scheduling strategy with respect to each EV.

Han et al. [35] designed an optimal aggregator by providing frequency regulation service to the power grid. Here, apart from the energy demander, EVs are also regarded as the supplier of frequency regulation service. Through a dynamic-programming-based approach, the optimal charging scheduling in terms of charging rate, charging sequence and charging duration is derived from revenue maximization. Utilizing a K-Nearest Neighbor classification to forecast the future electricity price, Erol-Kantarci and Mouftah [36] developed a prediction-based charging method, by determining the suitable charging time to achieve low operation cost.

Apart from centralized charging scheduling, the decentralized charging is also important. Gan et al. [37] proposed a decentralized EV charging scheduling algorithm, by applying broadcast control signals and asynchronous computation to satisfy the valley-filling electricity demand. Through a decentralized optimization algorithm based on convex relaxation optimization, Wen et al. [38] utilized a charging selection concept, to maximize user convenience and meet demand restrictions. Here, the user convenience is defined according to waiting time, SOC and charging cost.

[Integration With Renewable Energy Sources]

Although EVs can significantly reduce carbon dioxide emissions, conventional energy sources such as fossil fuels are still essential for power generation. Therefore, integrating with RESs such as solar, wind, hydropower, etc., can play a crucial role as an alternative power source for EV charging to reduce dependence on conventional energy sources. However, considering climate variation, the power generation based on RESs is highly uncertain. Therefore, the charging scheduling problem integrated with RESs is more complicated in terms of uncertainty.

El-Taweel et al. [39] investigated the CS operation optimization by considering multiple CSs and a photovoltaic (PV) farm simultaneously, where the energy generated by PV farm can be sold to CSs. Considering the impact of clean energy, the proposed scheduling and pricing strategy improves the profit of CS operator, while the price of EV charging is maintained at low level. Yan et al. [40] proposed a four-stage intelligent optimization and control algorithm, to alleviate the potential uncertainty of power consumption and generation, so as to reduce operation cost.

Table V. Summary of CS-Placement under Plug-in Charging Service

Year	Ref.	Methods & Techniques	Objectives
2011	[41]	Data mining	Best cover charging demand
2012	[42]	Particle swarm optimization	Minimize construct cost
2013	[43]	Data mining; Cross-entropy method; Multi-objective optimization	Maximize satisfaction of customers; Ensure stability of power grid

2) CS-Placement: The CS is the essential infrastructure to supply electrical energy to recharge EVs. A reasonable planning scheme for CS-placement can improve the QoE of EV drivers, and also benefit to CS's long-term operation, as categorized in TABLE V.

Frade et al. [41] investigated the deployment of slow charging facilities around Lisbon, where the utilization of residential and commercial is mixed. The placement of CSs aims to optimally cover the predicated demand based on a maximal covering model. Liu et al. [42] comprehensively investigated the impact of geographic information, construction and running cost. Based on the characteristic of non-convex, nonlinear and combinatorial optimization, the optimal planning of

CSs is determined with the proposed adaptive particle swarm optimization algorithm. Wang et al. [43] proposed a multi-objective CS planning scheme, to ensure the satisfaction of customers and the stability of power grid.

F. EV Drivers' QoE Optimization

The above analysis in Section II-E has been derived from the concerns of CSs. Besides, EV drivers are another indispensable part of the plug-in charging service. Considering the essential role of EV drivers, we introduce the following scenario from their perspective.

1) EVs to the Grid Supplement: The optimization problem of above charging scheduling from the view of CSs, is mainly regarded as the Grid to Vehicle (G2V) manner. Based on the application of bidirectional power flow transfer, EVs can also sell the residual energy to the grid for profit. In a G2V scenario, an EV only acts as an energy demand side. By contrast, an EV can supply energy to the grid with Vehicle to Grid (V2G) manner [44]. Apart from being an energy supplier, it can provide ancillary services such as frequency regulation and peak-load shifting. Although EVs can participate in the bidirectional power flow, the battery degradation on EV batteries due to frequent discharging should also be studied. Table VI compares related works reviewed herein.

Table VI. Summary of EVs to Grid Supplement under Plug-in Charging Service

Year	Ref.	Methods & Techniques	Objectives
2011	[45]	Heuristic algorithm	Maximize EV energy demand; Minimize charging cost
2012	[46]	Smart control method	Satisfy the convenience of EV drivers; Frequency regulation
2022	[47]	Particle swarm optimization	Alleviate pressure of power grid; Increase security of trade

Sortomme and El-Sharkawi [45] proposed a unidirectional regulation algorithm for an aggregator. The aggregator encourages EVs for transacting energy in the market, and uses several smart algorithms to determine the discharging rate. Ota et al. [46] developed an autonomous distributed V2G control strategy. Here, large-scale of RESs and battery energy storage are integrated into the power system with a smart charging control algorithm proposed. Yang et al. [47] considered the disadvantage of uncoordinated EV charging behaviors and DER generation for power distribution systems.

2) CS-Selection: Compared to the charging scheduling problem about when/whether to charge, here the focus of CS-Selection is on where to charge. This normally happens when an EV requires a charging service, it will drive towards the optimal CS under recommendation. Based on above analysis, it can observe that the optimization problem under the on-the-move mode is formulated as a CS-selection problem. In recent years, the EV charging optimization problem related to CS-selection has been attracting increasing attention. By combining the mobility characteristic of EVs, research is usually derived from the perspective of EV drivers. Table VII compares related works in CS-selection.

Table VII. Summary of CS-Selection under Plug-in Charging Service

Year	Ref.	Methods & Techniques	Objectives
2016	[48]	Data mining	Minimize recharging time
2016	[49]	Heuristic algorithm	Minimize service waiting time; Improve communication efficiency

Tian et al. [48] proposed a real-time CS recommendation system for Electric Taxis (ETs), so as to minimize charging cost and total charging time. The solution framework of the real-time recommendation system combines historical recharging events and real-time taxi GPS. Cao et al. [49] developed a vehicular-publish/subscribe communication framework for an EV to select the optimal CS, with potential to integrate with other public transportation infrastructures.

3) Routing and Navigation: The focus of routing and navigation aims to find a desirable route, from a location of EV towards the selected CS (determined by Section II-F2). Besides, it also aims to design an optimal route so that EVs can experience the shortest additional distance for recharging. Table VIII compares related works in routing and navigation.

Table VIII. Summary of Routing and Navigation under Plug-in Charging Service

Year	Ref.	Methods & Techniques	Objectives
2013	[50]	Empirical research method	Minimize charging waiting time
2014	[51]	Heuristic algorithm	Minimize service waiting time; Reduce driving distance of recharging

Lee et al. [50] investigated a tour-and-charging scheduling scheme for EVs in Jeju city, South Korea. Based on the trip schedule and charging waiting time, EVs can be charged while visiting tourist attractions, aiming to reduce the charging waiting time of customers. Lee and Park [51] proposed a distance-based heuristic algorithm to design a tour schedule for EVs selecting CSs. Different from [50] with limited number of CSs, the work in [51] considers the increasing time complexity caused by the large density of CSs.

G. Gaps Between Academia and Applications

In literature [52], a novel pilot project about pricing and control mechanism to coordinate residential EV charging loads is introduced. As the advocator of fast-charging, Tesla has developed a super-charging project and deployed more than 40 thousand super-chargers over worldwide. By utilizing a charging power of 250kW, EVs can be recharged less than 15 minutes and the energy can support a 250km driving range [11].

Based on the analysis of charging service in [20], the gap between optimization model and practical applications of plug-in charging service can be summarized as follows:

- **Shortage of Parking Space:** It is usually assumed that there is enough space for accommodating EV parking and charging. However, as for most crowded residential complexes with multifamily high-rise buildings, finding fixed parking spaces to charge EVs is a challenging. Besides, the expensive land price limits the development of CSs in downtown.

- **Weak Distribution Grid:** In optimization model, the power grid is usually assumed with sufficient capacity. In fact, power distribution networks are vulnerable considering aging infrastructure. Besides, the behavior of EV charging is random and unordered. Thus, EV charging, especially with an ultra-fast charging power, causes an overloading for power grid.
- **Uncertainty of EV Arrival:** In practice, when an EV reaches a CS is impacted by actual traffic condition, therefore, necessary traffic sensing and monitoring technologies, equipments are required to deploy around the road.

III. OVERVIEW OF BATTERY SWAPPING SERVICE

A. *Introduction of Battery Swapping Service*

(a) A Typical BSS of NIO

(b) Typical Battery Swapping Operation

Fig. 7. Battery Swapping Mode for EVs

As the most popular alternative for plug-in charging mode, the concept of battery swapping can be traced back to 1896 [53]. Moreover, the battery swapping technology was applied into practice by Hartford Electric Light Company in the early 1900s [54]. Until 2011, the first modern Battery Swapping Station (BSS) was created by Better Place Company in Israel and Denmark. Although the team was broken up in 2013, the novel energy supplement mode inspired subsequent commercial companies [55]. Based on developing technologies related to EVs, the population of BSS has grown rapidly in recent years. As an example in Fig. 7, NIO [56], as an advocate of battery swapping service, has built more than 900 BSSs by April, 2022. Unlike NIO mainly focused on private vehicles, Aulton provides battery swapping services for Electric Taxis (ETs) and plans to deploy 5000 BSSs by 2025 [57]. Under battery swapping service, depleted batteries are removed from EVs, and a refilled battery is replaced within 3-5 minutes. This operation costs a similar amount of time, compared with the ICE enabled vehicles refilling up the tank. Finally, depleted batteries are managed locally or by a third party to recharge for incoming EVs.

B. *Potential Risks of Battery Swapping Service*

Although the battery swapping service mode indeed exhibits great excellence, potential risks should also be noticed.

Users Convenience: Compared with the plug-in charging service, the battery swapping service can significantly reduce the waiting time. However, it is based on the ideal assumption that there are adequate inventory batteries for incoming EVs. Otherwise, long charging waiting time is still inevitable for depleted batteries becoming available. Besides, considering the land property value, BSSs are usually deployed in suburban districts. Thus, users have to drive a long distance for energy supplements. Moreover, considering service congestion (due to shortage of batteries available for swapping) at BSSs, a reasonable BSS-Selection mechanism is necessary to achieve load balance.

Initial Investment: The battery swapping service can indeed reduce electricity costs through battery charging optimization. However, the expensive BSS construction cost is inevitable, such as expenditure on batteries and equipment.

Interchangeability: Considering battery size and capacity, brand compatibility and cross-platform features cannot be neglected. That is to say, a specific type of EV is only compatible with the matched type of battery, and this inevitably increases inconvenience if there is no compatible battery at BSS. Therefore, the battery heterogeneity and cross-platform compatibility should be carefully addressed, so as to accelerate the development of battery swapping service.

C. *Benefits of Battery Swapping Service*

Similar with service objectives of plug-in charging in Section II-D, the battery swapping service implements the basic optimization involved in multi-party stakeholders. Besides, the battery swapping service can also utilize the similar decision framework of plug-in charging service (already reviewed in Section II-B), so as to achieve service optimization. Moreover, the battery swapping service exhibits remarkable superiority compared with plug-in charging mode, which can be summarized as follows:

From EV drivers' perspective, the battery swapping service can effectively reduce the energy supplement duration, alleviate range anxiety and improve QoE. Moreover, EV drivers will no longer to concern the battery degradation problem. This is mainly due to the business model of battery swapping, where both EV manufacturers and battery operators share the market by separating the battery and vehicle.

From the BSS operator's perspective, the battery swapping service can reduce the operation cost, by charging batteries in advance at the valley electricity price periods. Differing from the plug-in charging service with uncertain charging behavior, the battery swapping service can balance service demand and charging process by providing inventory batteries. Therefore, the demand of EV drivers can be guaranteed, while the operation cost can be reduced.

From the power grid's perspective, depleted batteries are managed by the BSS operator. The disordered charging behavior of individual users under plug-in charging service can thus be avoided. Therefore, the stability of power grid can be achieved with the cooperation of BSSs. Besides, depleted batteries are regarded as a static load connected to the power grid. The battery swapping service can further help to implement peak-load shifting, through charging and discharging behaviors of depleted batteries.

From the government's perspective, the battery lifetime can be extended by regular testing and maintenance. Besides, the battery swapping mode facilitates the recycling of batteries.

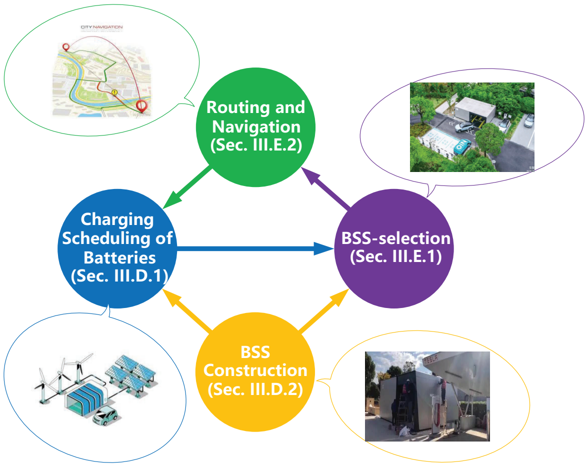


Fig. 8. Relation of Service Optimization under Battery Swapping Service

Compared to plug-in charging service, stakeholders under battery swapping service include the BSS operator and EV drivers. Then, the operation optimization at BSSs is presented from the construction to charging scheduling. The relation of application scenarios under battery swapping mode is depicted in Fig. 8.

Here, Fig. 9(a) shows optimization category under battery swapping service, while Fig. 9(b) shows the literature year on battery swapping service optimization based on our review. It is observed that the battery swapping as an emerging service model, has been receiving increasing attention since 2018. In the following review of this section, we decouple our understanding into **BSS Operation Optimization** for service operator's angle and **EV Drivers' QoE Optimization** for client's angle.

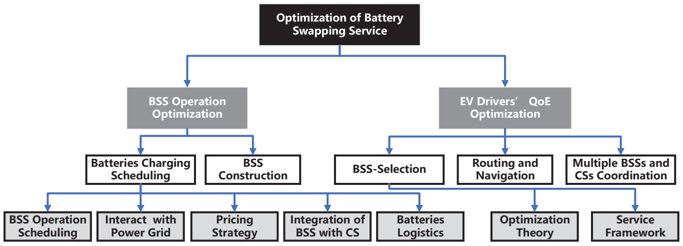
D. BSS Operation Optimization

1) Batteries Charging Scheduling: Batteries at each BSS can be regarded as a static load connecting to the power grid. Therefore, the focus of battery charging scheduling at BSS can be achieved through battery charging regulation. Table IX compares related works in charging scheduling of batteries.

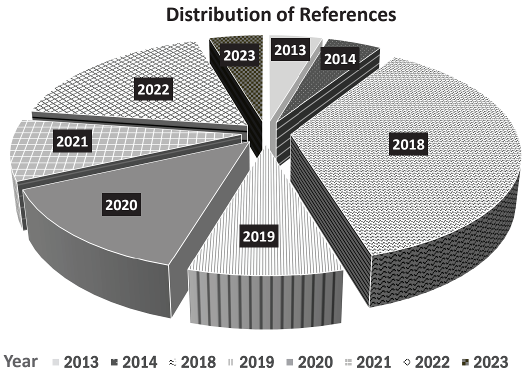
[BSS Operation Scheduling]

As for BSS operation scheduling, the BSS operator arranges optimal charging scheduling, based on the service requirements of incoming EVs and availability of batteries. The target is to maximize the profit for BSS operation and satisfy the demand for EV drivers.

Facing large-scale swapping demands during a day, authors in [58] considered the Constant-Current/Constant-Voltage (CC-CV) model to depict the actual charging process. The optimal charging scheduling based on different kinds of charging rates is proposed to minimize BSS operation cost. Literature [59] investigated the optimal charging and discharging process. Then, a robust optimization method is developed to find the optimal solution with the aim of minimizing electricity and battery degradation cost. Wu et al. [60] considered the charging scheduling problem, in terms of different charging rates under multiple battery types. Based on the greedy search method, a dynamic charging scheduling method is proposed to maximize the diversity of multi-type batteries.



(a) Optimization Category under Battery Swapping Service



(b) Literature under Battery Swapping Service Optimization

Fig. 9. Overview of Battery Swapping Service Optimization

Table IX. Summary of Batteries Charging Scheduling under Battery Swapping Service

Year	Ref.	Methods & Techniques	Objectives
2018	[58]	Differential evolution	Minimize BSS operation cost
2019	[59]	Robust optimization	Minimize BSS operation cost
2022	[60]	Greedy search	Maximize the diversity of batteries
2021	[61]	Deep Q network	Providing fast frequency services; Improving profits of BSS
2019	[62]	Integer linear programming	Minimize daily charging cost; Peak-load shifting
2020	[63]	Machine learning	Maximize the use of solar energy
2022	[64]	Bi-level optimization	Minimize electricity cost and waiting time
2018	[65]	Real-time pricing mode	Maximize global benefits
2022	[66]	Nash bargaining theory	Minimize BSS operation cost
2018	[67]	Queuing theory	Minimize charging cost
2019	[68]	Stackelberg theory	Maximize utility
2019	[69]	Alternating direction method of multipliers	Maximize profits

[Interactive Charging Scheduling with Power Grid]

Considering the high power demand of BSSs and the energy storage characteristic of batteries, a reasonable charging scheduling method interacted with the power grid is necessary. Accordingly, depleted batteries can be charged at the valley electricity price to reduce operation cost. Besides, BSSs can transmit battery energy back to the grid at peak periods. Through above interaction, the profit of BSSs and stability of power grid can both be improved.

Wang et al. [61] developed a dynamic scheduling strategy at BSSs, for providing fast frequency regulation services to the power grid. Due to the non-convex and random characteristics of optimization problem, a well-trained Deep Q-Network is proposed for optimal scheduling. Yang et al. [62] utilized the energy storage property of batteries in the BSS, providing auxiliary services with the Battery to Grid (B2G) method. Considering the power fluctuation and QoE of battery swapping service, a coordinated charging mechanism for the BSS in microgrid is proposed to minimize electricity costs.

Moreover, RESs are an important supplementary of the power grid during BSS operation, including solar and wind power. RESs are clean, inexhaustible and renewable, have been attracted increasing attention from the academic and industrial communities. However, it should also be noticed that RESs may face an uncertain problem mainly due to the climatic factor. Therefore, the uncertainty of RESs should be carefully addressed by effective charging scheduling to maximize the utilization, while the QoE of battery swapping can also be guaranteed.

Applying machine learning methods with feature extraction and model training, Feng et al. [63] proposed a BSS operation model integrated with PV generation. Combining the prediction information and traffic flow, a nonlinear programming strategy is proposed to reduce operation cost, achieve peak-load shifting and maximize the use of solar energy.

[Pricing Strategy]

The pricing strategy is one of the most important factors during BSS operation management. From the perspective of EV drivers, they prefer a lower service price regarding battery swapping service with undesirable QoE, i.e. long waiting time. By contrast, they also accept higher service pricing for better service QoE. In the light of this, a reasonable pricing strategy is significant for the BSS operator. Considering profit maximization, it may prefer to provide battery swapping service at a high price, and purchase energy from the power grid at a low price. Moreover, a proper pricing strategy can encourage BSSs to sell the residual energy through battery stocks, so as to help maintain the stability of power grid.

Ding et al. [64] investigated the coordination mechanism between autonomous mobility-on-demand system and BSS. The swapping pricing is dynamically adjusted based on the number of available batteries, so that EVs can move towards the BSS with a shorter waiting time. Liang et al. [65] proposed four battery swap pricing scenarios and two charging strategies for BSSs. Finally, the optimal scheduling and pricing strategies are developed to reduce carbon emissions and maximize all benefits of stakeholders.

[Integration of BSS with CS]

CSs and BSSs are usually investigated separately. That is to say, it is assumed that only CSs or BSSs exist in scenarios with optimization target for a single type of stakeholder (CS or BSS operator). In this part, the coordinated consideration of CSs and BSSs is introduced. A hybrid of these two types of stations are integrated, with the function of battery swapping and plug-in charging under this service mode. When an EV arrives at the station, the driver can choose the battery swapping or charging service based on the personalized demand, such as waiting time and service cost.

Zhong et al. [66] investigated a cooperative mechanism for CS and BSS in a microgrid to reduce operation cost. Considering the important role of CS and BSS in electricity and carbon trading, the optimization problem related to operation revenue is formulated based on Nash bargaining theory. Sun et al. [67] proposed an optimal operation strategy for a Battery Swapping and Charging Station (BSCS) to simultaneously reduce the electricity cost and ensure the QoE of EV drivers.

[Batteries Logistics]

The battery swapping service is usually based on the premise that depleted batteries can be charged at BSSs. However, the operation of swapping and charging at different stations respectively is also widely existed. In this case, depleted batteries swapped at BSSs, can be transported to Battery Charging Stations (BCSs) for recharging. Meanwhile, available batteries are carried from BCSs back to BSSs for providing services for incoming EVs.

Based on game theory, Zhao et al. [68] introduced a closed-loop supply chain management method to realize optimal day-ahead scheduling of BSCS. Considering the coordination of BCSs and BSSs, Liu et al. [69] proposed a closed-loop supply chain based BSCS. Specifically, the battery swapping service is modeled as a network calculus-based service, and a time-space network model is introduced for battery logistics.

Table X. Summary of BSS Construction under Battery Swapping Service

Year	Ref.	Methods & Techniques	Objectives
2013	[70]	Multi-criteria decision making	The optimal position of BSS
2014	[71]	Monte Carlo sampling	The optimal configuration of BSSs

2) BSS Construction: The BSS construction is complementary in addition to service optimization. This part mainly analyzes the BSS initial operation planning, including BSS-placement and configuration. Table X compares related works in BSS construction.

The BSS placement problem is defined as locating and deploying a BSS at a certain place over the city district. Since the location of BSS is fixed but with increased investment cost, the construction of BSS should be determined with sufficient investigation based on the quantity of EVs, land price, distance and power grid.

Since BSS-placement plays an important role in subsequent operations, Wang et al. [70] proposed a BSS-placement framework based on multi-criteria decision making, including upfront investment, impact on power grid and service QoE of EV drivers. Schneider et al. [71] investigated the configuration optimization problem of BSSs with charging slots and batteries. The aim is to obtain the optimal equipment configuration of BSS operation, considering the battery swapping requirements and electricity price.

E. EV Drivers' QoE Optimization

Table XI. Summary of BSS-Selection under Battery Swapping Service

Year	Ref.	Methods & Techniques	Objectives
2018	[72]	Queuing theory; MDP	Performance analysis of BSS operation
2018	[73]	Second-order cone programming relaxation; Generalized Benders decomposition	Minimize a weighted sum of EVs' travel distance and electricity generation cost
2018	[74]	Monte Carlo sampling; Alternating direction method of multipliers	Minimize a weighted sum of EVs' travel distance and electricity generation cost
2021	[75]	Heuristic algorithm; Queuing theory	Minimize service waiting time
2022	[76]	Heuristic algorithm	Balance service waiting time and battery degradation cost
2023	[77]	Heuristic algorithm; Long Short-Term Memory Network	Minimizing service waiting time; Reducing BSS operation cost

1) BSS-Selection: In the batteries charging scheduling (Section III-D1), the optimization strategy on BSS operation has been presented, with concern on when and which battery to charge. By contrast, the BSS-selection problem is devoted to recommending the optimal BSS to EV drivers. Here, the optimal BSS is selected according to various criteria, such as minimum service waiting time, lowest service cost and shortest travelling distance. Table XI compares related works in BSS-selection.

[Optimization Theory]

Due to the limited available batteries and charging slots of BSSs, incoming EVs usually have to wait until a depleted battery becomes available. Considering the arrival rate of EV flows and the service ability of BSSs, the service process can thus be transformed as a queuing theory problem. Besides, since the optimization objective function is usually formulated with waiting time and service cost, the optimization problem can thus be solved from the field of mathematical optimization.

Based on the battery swapping and charging process, Tan [72] et al. proposed a queuing theory method to assess the service performance of a BSCS. To be specific, a mixed queueing network model consisting of an EV queue and a battery queue is designed. You et al. [73, 74] investigated the optimal BSS assignment with a centralized and distributed manner, so as to minimize a weighted sum of EVs' travel distance and electricity generation cost. For centralized implementation, a solution based on second-order cone programming relaxation of optimal power flow and generalized Benders decomposition is proposed with global information [73]. By contrast, two distributed solutions based on alternating direction method of multipliers and dual decomposition are proposed with distributed manner in literature [74].

[Service Framework]

Although a global optimal solution can be achieved, they are usually derived with the ideal assumption that the global demand information is known in advance. Considering this disadvantage, the service framework is proposed in practical application scenarios.

With the development of Information and Communications Technology (ICT), Cao et al. [75] developed a Mobile Edge Computing (MEC) driven battery swapping service management scheme. Utilizing the public transportation bus integrated with MEC server collects EVs' reservations and transmits BSS status to EVs, the EV driver can move towards the optimal BSS with the shortest waiting time. Apart from the waiting time for EV drives, Li et al. [76] also considered the impact of battery degradation cost from the perspective of BSS operator. The joint optimization between EV drivers and the BSS operator can be achieved through the demand balance battery swapping service framework. Besides, considering battery heterogeneity, a coordinated battery swapping service management is developed in [77]. Under the proposed optimized operation mechanism of available slots allocation and service demand forecast, EV drivers can drive to the BSS with minimal service time, meanwhile reducing BSS operation cost.

2) Routing and Navigation: The routing and navigation optimization problem is mainly derived from the optimal path planning when a target BSS is selected (detailed referred to Section III-E1). Considering the route limitation, EVs aim to find a BSS for energy supplement with the minimum cost in routing process. This is common for ETs service process that drivers should achieve fast battery swapping service to meet seamless journey demand for customers, in order to maximize profit. Table XII compares related works in BSS routing and navigation.

Table XII. Summary of Routing and Navigation under Battery Swapping Service

Year	Ref.	Methods & Techniques	Objectives
2018	[78]	Dynamic routing method; MDP	Maximize social welfare
2018	[79]	Population-based method; Local search method	Minimize routing costs; Minimize BSS operation costs

Due to the limited battery capacity, ETs have to select a BSS for energy supplement during pickup and drop-off tours. Based on above scenario, Sayarshad et al. [78] developed a dynamic routing method based on Markov Decision Process (MDP) with elastic demand to maximize social welfare. Considering the interaction between EVs and BSSs, Masmoudi et al. [79] defined an EV Dial-a-Ride problem. It focuses on scheduling a fleet of EVs to satisfy pre-specified service requests.

3) Multiple BSSs and CSs Coordination: Under multiple BSSs and CSs service mode, BSSs and CSs are operated independently. A certain number of BSSs and CSs are located around the city, where a station can only support battery swapping or charging service. EV drivers with energy supplement demand, will move towards a BSS or a CS according to the station recommendation. Table XIII compares related works in multiple BSSs and CSs coordination.

Table XIII. Summary of Multiple BSSs and CSs Coordination under Battery Swapping Service

Year	Ref.	Methods & Techniques	Objectives
2020	[80]	Multi-objective optimization; Weight coefficient method	Maximize global benefits
2020	[81]	Heuristic algorithm	Minimize service waiting time

Utilizing MATLAB and MATPOWER, Luo et al. [80] developed a simulation platform for a large-scale traffic flow and proposed an EV charging scheduling scheme for different types of EVs. Considering the deployment of BSSs and CSs over the city, choosing a charging or battery swapping service depends on service waiting time, traveling distance and real-time road condition. According to the operation scenario of ETs, Zhang et al. [81] developed a reliable ICT-enable holistic charging management framework to support integration of plug-in charging and battery swapping service. With the proposed framework, the optimal decision between CS and BSS can be determined based on two types of service queue analysis to experience the shortest trip.

F. Gaps Between Academia and Applications

As for public transportation, in 2008, a BSS and 50 electric buses are serviced for the Beijing Summer Olympics. It was the first modern, intelligent BSS in the world. Benefiting from the environment-friendly and convenient energy supplement technology, in 2010, similar systems were deployed at the Shanghai World Expo and the Guangzhou Asian Games [20]. Nowadays, the battery swapping based electric bus is widely applied in public transportation [82]. As for EVs, the Better Place Company has constructed the world's first BSS for taxis in Tokyo [83]. Since 2000, the Alton Company has devoted to providing an integrated battery swapping service for various brands EVs. It has serviced for more than 44.14 million EVs until January 2023 [57]. Besides, NIO has deployed more than 1300 BSSs across China, serving for NIO drivers [56].

Based on the analysis of battery swapping service in [21], the gap between optimization model and practical applications of battery swapping service mode can be summarized as follows:

- **Interchangeability:** Considering the size, battery capacity and parameter characteristic, batteries are generally incompatible among diversity of EVs and BSSs managed by different operators. Therefore, the compatibility is a huge gap between optimization model and practical applications.
- **Initial Investment:** As for the operation of a BSS, abundant battery packs are essential. Besides, a huge initial investment on battery swapping operation machine is necessary. Moreover, considering the high-load of depleted batteries charging, the reconstruction of power grid is also concerned. Thus, the initial construction investment is a non-negligible in practical application.

IV. OVERVIEW OF V2V CHARGING SERVICE

A. Introduction of V2V Charging Service

Unlike the traditional plug-in charging service, a flexible V2V charging service is proposed in [84] to allow a pair of EVs to transfer energy between each partner. The V2V charging service allows energy transfer from EVs with energy supplies to those with energy demand, in convenient and economic manner. Besides, the V2V charging service does not occupy grid resources during peak charging period. Therefore, it can also be used to balance the load of grid and reduce the adverse impact of grid during peak hours.

The dual-input single-output DC-DC converter was proposed in [85] for enabling the V2V charging service. Roberts et al. [86] proposed a progression of confirmation protocols to be utilized for V2V charging service. The fundamental inspiration is to get EVs charged using existing norms like dedicated short range communication, Wi-Fi Direct or Bluetooth. Authors utilized a common key trade convention that doesn't depend on testaments for confirmation. Then, they proposed conventions utilizing cell phones and Wi-Fi Direct conventions.

There are mainly two application scenarios under the V2V charging service, with the direct V2V charging and the asynchronous V2V charging manners. Usually, with the direct V2V charging manner, EVs are divided into pairwise energy providers and energy consumers. Through the energy transfer devices (such as DC-DC converters [85]), energy can be transferred from energy providers to energy consumers [86, 87]. Besides, the accumulators at Power Storage Stations (PSSs) can store energy of energy providers, and transmit energy to energy consumers that need charging. Thus, with the asynchronous V2V charging manner, the charging and discharging do not require both parties to start at the same time.

B. Potential Risks of V2V Charging Service

Here, we briefly summarize the potential risks of V2V charging service.

The Mismatch of Charging & Discharging: The V2V charging may fail due to mismatch of charging protocol among heterogeneous EVs in the market.

Privacy Issues: The V2V charging service requires privacy sensitive information of pairwise EVs including location and driving route. The leakage of such information will affect the security of users.

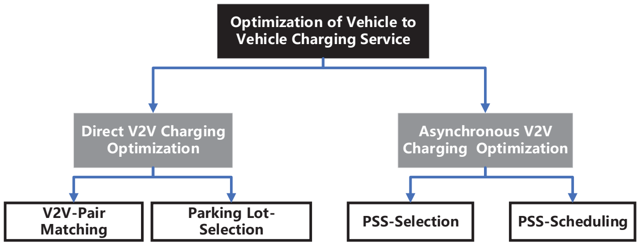
Slow Charging Speed: The V2V charging is flexible in the temporal domain, and avoids the problem of long charging waiting time at CSs. However, it is noted that the charging power, between energy consumers and energy providers under V2V charging service, is much lower compared to that under the plug-in charging service.

C. Objective of V2V Charging Service Optimization

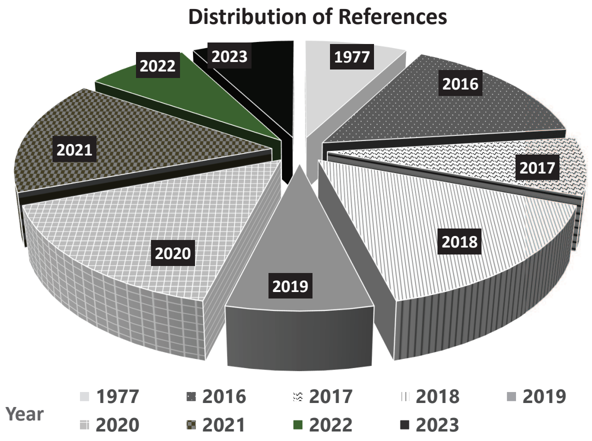
The V2V charging service is flexible in the temporal domain (depends on the available time of EVs other than the available time of CSs), avoids the charging time of EVs not matching the free time of CSs. Besides, it is flexible in the spatial domain (depends on choosing a parking lot with an available parking space), avoids selecting fixed-position CSs.

Here, the optimization of V2V charging service is normally modelled as a constrained MILP. In literature [84], through dual decomposition and benders decomposition, the distributed algorithm is used to solve the problem. Chakraborty et al. [88] introduced a cloud-based control system to match V2V charging pair and optimize charging service. At the hardware level, Ucer et al. [89] investigated the potential of bidirectional DC-DC converters for V2V charging service. Meanwhile, by deploying converters, traditional parking lots can be facilitated for V2V charging service [90]. This literature proposed a new perspectives on V2V power transmission via AC and DC, with the emphasis on V2V power transmission using DC power supply.

The objective of the V2V charging service determines the optimization problem consensus and decision-making behavior of different service participants. Here, we further analyze this objective from the perspective of both the provider and the consumer.



(a) Optimization Category under V2V Charging Service



(b) Literature under V2V Charging Service Optimization

Fig. 10. Summary of V2V Charging Service Optimization

From the perspective of energy consumers, the range anxiety and service QoE are major concerns. Besides, the charging cost is another key factor that energy consumers consider. Here, the cost typically includes two aspects: travel costs and fees paid to the energy provider.

From the perspective of energy providers, they want to sell their excess energy to energy consumers. Therefore, selling price and travel costs are key issues to consider.

From the perspective of parking lots/PSS, an effective scheduling strategy is required to plan the charging/discharging sequence of EVs.

Fig. 10(a) illustrates the optimization category of V2V charging service, while and Fig. 10(b) shows the literature year on V2V charging service optimization. Obviously, such flexible service model has been given continuous attention in recent years. In the following review of this section, we decouple our understanding into **Direct V2V Charging Optimization** and **Asynchronous V2V Charging Optimization** depending on the service features.

D. Direct V2V Charging Optimization

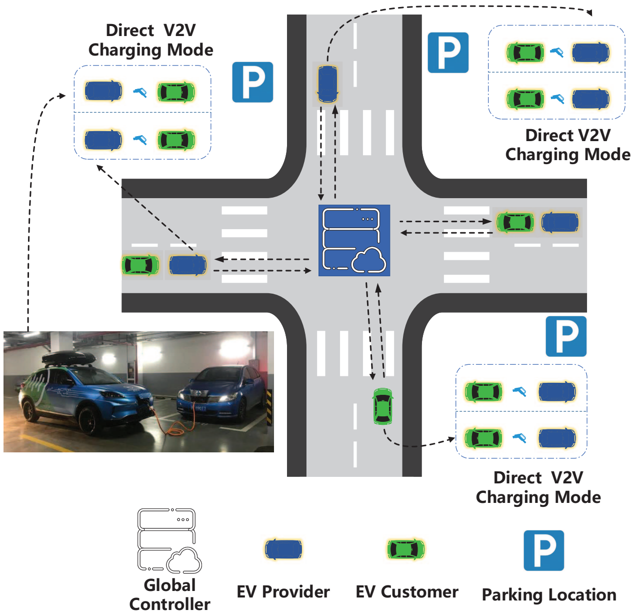


Fig. 11. Illustration of Direct V2V Charging Mode

In Fig. 11, a typical procedure for V2V charging is introduced. The system is controlled centrally by GC, including information collection and global planning. Based on the global planning, energy consumers and energy providers can travel to parking lots for V2V charging service according to their preferences.

Under the direct V2V charging service, when an EV customer requests for charging, it requires an adequate energy provider to match for a maximized charging utility and minimized charging cost. Therefore, the optimization framework for direct V2V charging are divided into two main categories shown in Fig. 12.

1) V2V-Pair Matching: The V2V-Pair Matching aims to rank a pair of EVs to perceive charging service with P2P manner. Here, the following constraints should be noted: (a) If the subsequent travel of energy providers is considered, the residual energies of energy providers need to meet the minimum requirement of completing their travels. (b) The energy transfer of EVs providers will cause additional energy loss. Table XIV compares the related literature.

Bulut et al. [87] proposed a V2V charging system to permit V2V energy transferring. EV drivers with range anxiety can

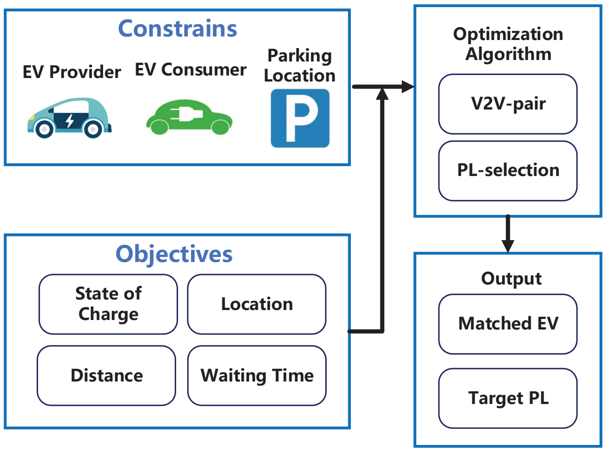


Fig. 12. Optimization Framework of Direct V2V Charging

Table XIV. Summary of V2V-Pair Matching under Direct V2V Charging Mode

Year	Ref.	Methods & Techniques	Objectives
2017	[87]	Maximum weighted diplot matching	Optimize pair matching between EVs
2020	[91]	Integer linear program	Maximize the served number of EVs
2020	[92]	Mixed integer optimization; Gale-Shapely algorithm; Stable marriage algorithm	Minimize the total charging cost
2021	[93]	Bipartite graph-based search; Subsystems of V2V charging	Schedule charge/discharge cycles between trading EVs
2016	[94]	Mixed-integer non-linear program	Optimize system efficiency
1977	[95]	Oligopoly game	Minimize EVs' charging costs
2022	[96]	Gale–Shapley matching algorithm	User satisfaction; Social welfare; Energy demands fulfillment; Users' privacy

purchase energy from EVs with excess energy to sell. EVs communicate with each other in proximity through a location based social networking system. Besides, this work uses a maximum weighted diplot matching algorithm to optimize pair matching between EVs. Kabir et al. [91] assumed a company having a number of V2V enabled charging trucks equipped with a larger battery and a fast charger. Authors formulated an Integer Linear Programming (ILP) to maximize the number of served EVs, by determining the optimal trajectory of each truck.

In literature [92], energy consumers are allocated to the optimal energy supplier (CS or energy provider) to minimize the total charging cost. The matching problem is described as a mixed integer optimization problem which is NP-hard, and solved with stable marriage algorithm.

Based on the marriage matching algorithm for V2V-pair matching [92], the classical Delay Acceptance Algorithm proves it [97]. Then, the problem is how to find a stable match effectively. In the stable marriage stage, the Gale-Shapley algorithm is an effective method for finding stable one-to-one matching in stable marriage. The algorithm for EV consumers generates the optimal stable matching. Among them, each EV as an energy consumer has its best matching partner in any stable matching, while the algorithm for EV providers generates the output of EV consumers. This property is called stable matched polarization [98].

Zeng et al. [93] proposed a bipartite graph-based search method, to facilitate power exchange in power distribution systems. The power distribution system is divided into a series of subsystems according to the location of EVs. The proposed bipartite graph-based search algorithm adopts charging models in EVs, to facilitate transactional V2V power exchange. In addition, with adaptively adjusting the respective energy transaction targets, the energy transaction price of a single EV can track the price of the subsystem.

Wang et al. [94] proposed an novel architecture to enhance the communication capability of EVs, through the smart grid enhanced by heterogeneous wireless networks. The motivation of EV with residual energy is to get paid to participate in a V2V energy exchange transaction. Based on the information collected from the EV and power grid, the aggregator determines the energy price of EV. The oligopoly game is used for the price control strategy [95] with competition among EVs. Using the published price, a mobility-aware spatiotemporal coordinated V2V energy exchange strategy is designed to realize the energy exchange between EV at the aggregator. The strategy is modeled as a time coupled MILP, which is decoupled into a series of sub-MILP by Lagrangian duality [99].

Shurrab et al. [96] proposed a novel integral V2V energy sharing framework. It consists of four layers, including key modules, models and technologies for developing efficient V2V solutions. The framework focuses on building a comprehensive V2V solution, which is not only cost-effective, but also can maintain high user satisfaction, social welfare and energy demand.

2) Parking Lot-Selection: In general, V2V-pairs need to select a parking lot as common place to operate energy transfer. Once the GC has conducted a feasibility analysis of parking lot-selection for V2V-pairs, the core factors are based on trajectory driving time, energy consumption, charging time and charging comfort quality. Once energy consumers and energy providers establish V2V-pair matching, they will need to address the problem of parking lot-selection.

In practice, EVs require an optimized parking lot-selection, due to the scarcity of parking resources. Besides, parking lots may not supply sufficient equipments/chargers for V2V charging service. However, only a few previous studies have considered the problem of parking lot-selection along with V2V-pair matching [100], [101]. Table XV compares the literature related to parking lot-selection under the direct V2V charging mode.

Table XV. Summary of Parking Lot-Selection under Direct V2V Charging Mode

Year	Ref.	Methods & Techniques	Objectives
2018	[100]	Shortest path algorithm; Charging pleasure degree model	Travel energy cost; Charging pleasure; Minimize the charging cost
2019	[101]	Q-learning based algorithm	Optimal traveling route; Location for V2V charging

A communication framework based on VANETs is designed to realize real-time data transmission between CSs and EVs [100]. Through the derived travel energy cost and charging pleasure model, EVs are able to reserve the corresponding optimal parking lot to minimize the charging cost.

An intelligent V2V charging navigation strategy for EVs based on vehicle communication is proposed [101]. Firstly, an effective semi-centralized charging navigation structure based on MEC is established. It ensures the reliable billing information dissemination and feasible charging coordination, with low cost of communication and computation. Upon this, authors designed an effective local-to-global charging navigation mechanism, to dynamically select the driving route and parking lot for V2V charging operation.

E. Asynchronous V2V Charging Optimization

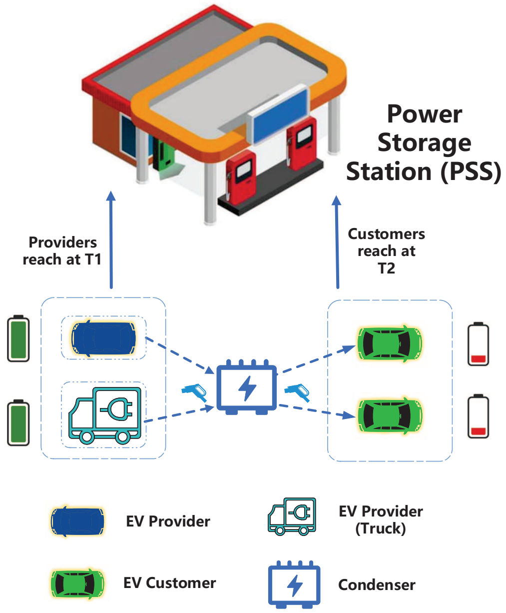


Fig. 13. Illustration of Asynchronous V2V Charging Mode

Since the majority of works under the direct V2V charging mode (Section IV-D) are with low charging rate under 20kW [89, 90], the charging time through direct V2V charging manner is extremely long. Meanwhile, the V2V charging service suffers from uncertainty of EV charging demand. Therefore, by introducing asynchronous V2V charging service, the above problem can be alleviated by decoupling the requirement in spatial and temporal dimensions.

Fig. 13 shows the asynchronous V2V charging service. Different from the direct V2V charging manner [100], under asynchronous V2V charging manner, an energy consumer and an energy provider do not have to start V2V charging simultaneously. Instead, energy providers deliver energy to the PSS equipped with condensers [102], to store energy, while the PSS can transfer energy to energy consumers when needed. The work [103] uses J1772 combo connectors between EVs to transfer energy with 60kW DC-to-AC power converters. Each EV is equipped with a vehicle communication module, to provide the information of energy exchanging.

Under the asynchronous V2V charging mode, when an EV customer requests for charging, it requires a suitable PSS for a maximized charging utility and minimized charging time. Therefore, the optimization problem is divided into two main categories showed in Fig. 14.

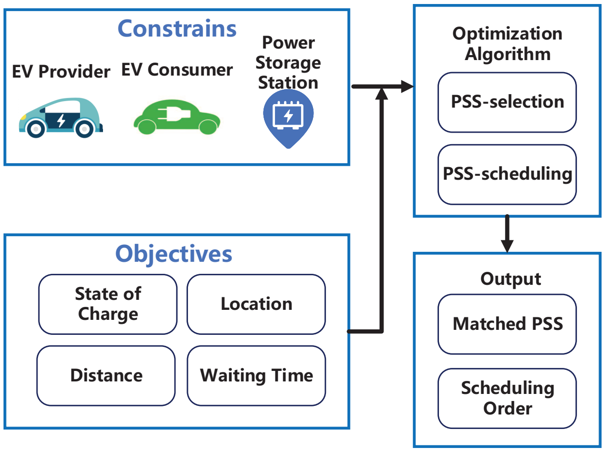


Fig. 14. Optimization Framework of Asynchronous V2V Charging

1) PSS-Selection: The following constraints should be noted: From the perspective of energy consumers, they want to recharge with a short charging service time. In addition, the charging price also needs to be considered. From the perspective of energy providers, they want to sell excess energy at a higher price. Besides, the energy consumption for travel also needs to be considered. Table XVI compares the literature related to PSS-selection under the asynchronous V2V charging mode.

Table XVI. Summary of PSS-Selection under Asynchronous V2V Charging Mode

Year	Ref.	Methods & Techniques	Objectives
2018	[104]	Matching game	Decrease range anxiety; Increase number of charged EVs
2023	[105]	Heuristic algorithm	Decrease average charging price per unit; Increase average energy charging; Decrease average waiting time; Decrease charging cost

Kim et al. [104] tackled range anxiety and limited charging spots, based on the matching theory (choosing sufficient energy supplier for energy consumers). In this paper, authors proposed the matching based method that can cooperate between V2G and V2V charging modes, to decrease range anxiety and increase number of charged EVs. Authors further investigated the proposal numerically, by comparing V2G and V2V charging mechanisms.

The work in [105] proposed a hybrid V2V and G2V modes. Here, EVs sending charging requests are centrally assigned by the GC, to charge at CSs via G2V mode or at parking lots via V2V manner. The optimal charging decision between CSs and parking lots is determined based on two types of service queue analysis, to minimise the charging cost of EVs. An analytical hierarchy process is applied to the charging cost calculation, where the charging waiting time, charging price and charging energy are weighted. In addition, a charging reservation approach is applied to perceive charging availability and guarantee driver QoE.

2) PSS-Scheduling: During PSS-scheduling, scheduling algorithms should be applied to efficiently schedule EVs to charge/discharge. Here, EVs in urgent need of charging should be given a high priority. Table XVII compares the literature related to PSS-scheduling under the asynchronous V2V charging mode.

Table XVII. Summary of PSS-Scheduling under Asynchronous V2V Charging Mode

Year	Ref.	Methods & Techniques	Objectives
2021	[106]	Primal-dual approximation algorithm	Minimize the social cost
2016	[107]	Integer linear programming	Low execution times

Yuan et al. [106] studied the EV charging scheduling problem with V2V auction and local generation under demand response. To encourage EVs to participate in energy supply, authors proposed an online auction mechanism based on a primal-dual approximation algorithm, to decompose the long-term social cost minimization problem into a series of single-round auctions. Furthermore, to avoid the cost caused by excessive switching of local generators, authors further designed an online algorithm based on the idea of delayed switching, which guarantees provable polynomial running time, authenticity, and individual rationality for each auction. Finally, real-world data was used to track and verify the practical superiority of the method over multiple existing algorithms.

Koufakis et al. [107] proposed an optimal EV charging scheduling scheme considering the cooperation between G2V and V2V modes. This work formulates the optimization using ILP and for problem solving in off-line manner. Furthermore, it introduces three different ideal arrangements for the EV charging planning problem, to support the movement of energy between EVs.

F. Gaps Between Academia and Applications

The global P2P EV charging market size was valued at USD 128927.3 thousand in 2022 and is expected to expand at annual growth rate of 22.3% from 2023 to 2030. Factors such as the growing demand for EVs worldwide and government policies, subsidies for purchasing EVs as well as charging infrastructures promotion, have led to an increase in the demand for P2P EV charging stations. According to a study by the European Association of Automobile Manufacturers, the Netherlands, Germany, and France collectively account for nearly 70% of the regions EV charging stations in 2020. Moreover, in 2020, EV sales in Europe grew by 89%, which is further expected to contribute to the growth of the market [108]. There has been an App for V2V charging service called EVmatch, available from App store in the USA [109].

The V2V charging service still poses several challenges for wide application, compared to plug-in charging and battery swapping service, due to following issues:

- **Lack of Third-party App:** A third-party App is essential in the V2V charging service because it enables two vehicles to communicate with each other and exchange information about their charging status, location, and availability. The App also needs to provide a secure platform for the charging parties to share their billing information and complete the payment process. Without this, the V2V charging service would be an unreliable and unorganized process, which could deter the adoption of the technology. To address this challenge, developers and stakeholders in the EV industry need to collaborate to create a robust and user-friendly third-party App. This App should have a simple user interface and provide real-time updates about the charging status of both EVs. It should also incorporate security features such as encryption and authentication to ensure the privacy and security of the charging parties' billing information.
- **Lack of Energy Providers:** Another major challenge facing V2V charging services is the lack of energy providers, especially in areas with a low concentration of EVs [100]. To address this challenge, stakeholders need to collaborate to create a robust and sustainable V2V charging ecosystem. One solution could be to encourage EV owners to participate in V2V charging networks, by offering them discounts on their energy bills. This would encourage more EV owners to participate, thereby increasing the number of energy providers in the V2V charging network. Another solution could be to establish partnership with businesses and organizations that have large fleets of EVs, such as ride-hailing services or delivery companies. These organizations could be encouraged to participate in V2V charging programs by offering them discounts on their energy bills, or by providing them with incentives such as priority access to CSs.
- **Lack of Governmental Policy:** Furthermore, governments could play a significant role in promoting V2V charging services by providing tax incentives to organizations that participate in V2V charging programs. Governments could also provide funding for the development of V2V charging infrastructure in areas where there are few EVs on the road.

V. OVERVIEW OF MOBILE CHARGING SERVICE

The above charging modes provide a wealth of opportunities to optimise EV charging. However, as the number of EVs continues to grow, the ratio of EVs to charging infrastructures (CS and BSS) is still far from adequate. To alleviate range anxiety and improve charging convenience, mobile charging service becomes a new perspective for research. Fig. 15 shows the illustration of mobile charging application.

A. Introduction of Mobile Charging Service

Considering that EVs are with high mobility, there is a great potential for EVs to be charged via mobile charging. Mobile charging involves MCSs (as opposed to fixed charging infrastructure) and in-motion EV charging by Mobile Charging Truck (MCTs) or other private EVs. As such, mobile charging has greater potential for application in temporary charging

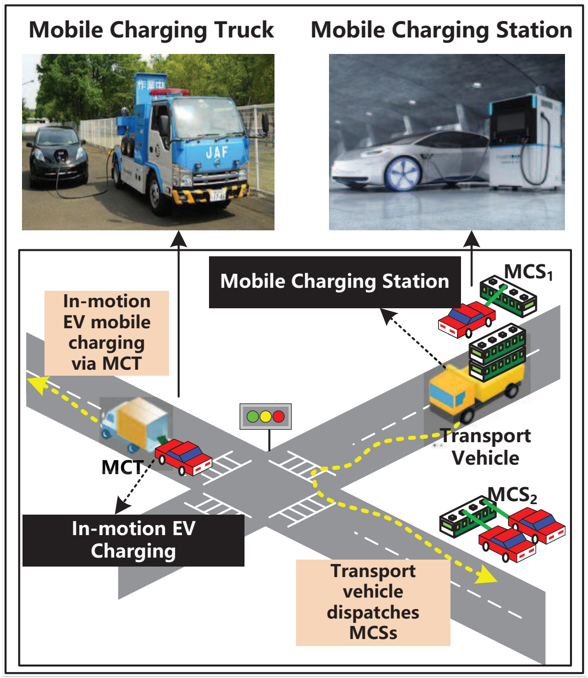


Fig. 15. Illustration of Mobile Charging Service

or emergency roadside assistance. There are currently two categories of mobile charging:

Mobile Charging Station (MCS): Unlike Fixed location Charging Stations (FCSs) deployed at fixed locations, MCSs can be dispatched by transport vehicles to changing addresses for charging. Battery Energy Storages (BESs), as the main component of MCSs, are towed or carried by transport vehicles.

In-motion EV Charging: When an EV determines that it needs to get charging service as soon as possible, it sends a charging request. Other EVs (MCTs or other private EVs) that are aware of this signal can provide the service. EVs are continuously charging by wired or wireless approach while driving.

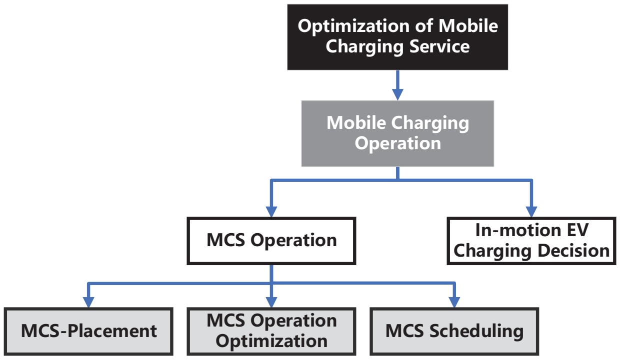
B. Potential Risks of Mobile Charging Service

Although mobile charging has a huge application potential, it is still subject to a number of constraints:

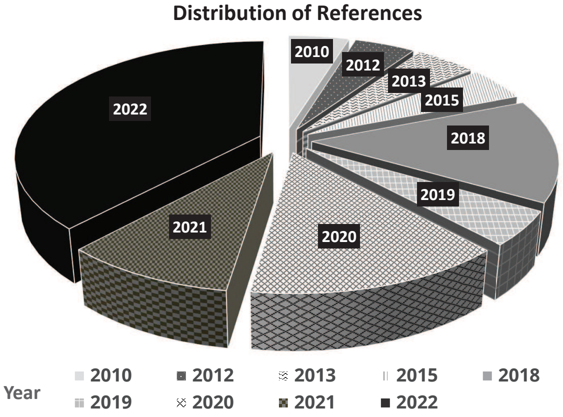
Operational Management: The current EV penetration rate is not high enough, the economic benefits of deploying and operating MCSs will be smaller than those of FCSs [110]. Meanwhile, as some MCSs are dispatched to remote areas, it is difficult to carry out periodic checks on them at short frequencies. This leads to physical uncertainties, making MCSs more difficult to manage. Furthermore, MCSs still face the impact of battery degradation levels on BES life expectancy [111].

Privacy Protection: Due to high frequency data interaction in mobile charging management, this places a high demand on privacy protection during communication. A large amount of private EV data (e.g. location, vehicle ID) is included, thus MCSs operator needs to ensure that the data is protected during transmission and utilization.

C. Benefits of Mobile Charging Service



(a) Optimization Category under Mobile Charging Service



(b) Literature under Mobile Charging Service

Fig. 16. Overview of Mobile Charging Service Optimization

Mobile charging is more flexible than FCS in terms of location. The MCS mode is designed to relieve energy pressure in 'hot spot' areas, while the in-motion EV charging mode provides differentiated charging services specifically for EVs (e.g. roadside assistance).

From EV driver's perspective, the lack of charging infrastructure in most remote areas (suburban or rural) makes it difficult for EVs to find charging facilities. However, the MCS mode allows temporary deployment and increases the supply of charging infrastructure in remote areas.

From the grid perspective, the use of MCS can effectively reduce the investment cost of grid charging facilities. On the one hand, as a flexible mobile charging mode, mobile charging can effectively reduce the driving time of EVs. On the other hand, mobile charging can be used in emergency charging scenarios such as roadside assistance (charging EVs with depleted batteries). In addition, MCS with storage capacity can be recharged during off-peak hours, allowing them to provide energy during peak hours, thereby relieving pressure on the grid [112].

Here, Fig. 16(a) shows the optimization category under mobile charging service, while Fig. 16(b) shows the literature year on mobile charging service optimization, as recent literature can be investigated up to 2022. In the following review of this section, we focus on **Mobile Charging Operation** for the service operator's angle.

D. Mobile Charging Operation

The V2V charging optimization focuses on the requirement for users to optimize EV drivers' QoE, while the mobile charging optimization focuses on service providers. Therefore, the operational deployment of MCSs is crucial.

1) MCS Operation: There are currently two issues for MCS operation. To ensure the QoE of EV drivers, the deployment of MCSs needs to be optimised. To minimise the operating costs of MCS operators, optimization of MCS scheduling, charging reservation and charging pricing need to be considered. Table XVIII compares related works in MCS operation under mobile charging service.

Table XVIII. Literature Related to MCS Operation under Mobile Charging Service

Year	Ref.	Methods & Techniques	Objectives
2010	[113]	Iterative computing	Reduce charging waiting time; Improve success rate of MCS services
2013	[114]	Dynamical programming	Reduce charging waiting time
2021	[115]	Queueing model; Quadratic Assignment Problem - Ant Colony Optimization (QAP-ACO)	Reduce charging waiting time; Relieve FCS load pressure
2018	[116]	Data analysis	Reduce charging waiting time; Maintaining load balancing at stations
2018	[117]	Mixed integer non linear programming; Oligopoly game	Reduce average EV driving costs; Increase number of charged EVs; Increase charging power
2020	[118]	Two-stage stochastic optimization	Reduce average EV driving costs; Reduce MCS operating costs
2018	[119]	Mixed integer linear program; Routing with time windows	Guarantee the number of charging services; Reduce total travelling distance
2020	[120]	Mixed integer linear program; Auxiliary induced function	Rehabilitate grid line
2022	[121]	Auction game	Guarantee fairness of mobile charging system
2020	[122]	Queue optimization	Reduce operation cost; Reduce battery capacity cost
2015	[123]	Queue optimization; Nearest-job-next service policy	Reduce charging waiting time; Optimize battery capacity with a threshold charging rate
2018	[124]	Mixed integer linear program	Reduce total distance travelling of transport vehicles
2021	[125]	Mixed integer linear program; Dantzig-Wolfe decomposition	Maximize the number of served EVs; Reduce charging price
2020	[126]	Heuristic algorithm	Reduce charging waiting time; Increase the number of EVs fully charged
2022	[127]	Analytical hierarchy process; Mixed integer linear programming	Guarantee power supply; Maintain load balancing on the grid

[MCS-Placement]

The deployment of MCS can alleviate charging pressure in 'hotspot' areas and provide flexible charging options in locations that are not suitable for permanent FCS deployment. The work in [113] proposed a nomadic MCS concept, it looked at the impact of the number of MCSs in a region and the ratio of EVs to MCSs on the probability of outages and charging delays. The EV charging waiting time was reduced by MCSs deployment through a proposed mobile charging information management system in [114]. It allocates MCSs based on information about the charging density of FCSs. This allocation takes into account EV arrival queues, request queues. In [114], a multi-queue scenario is applied to optimize the mobile charging service provided to EVs. The work in [115] modelled the dispatch of MCSs as a constrained optimization problem and proposed a heuristic solution. Here, a meta-heuristic solution based on an ant colony optimization algorithm is considered. A greedy algorithm was proposed in [116] to allocate MCSs. Here, the MCS with the most excess energy is allocated to the locations where the energy demand is the highest, helping to maintain load balance in the grid.

[MCS Operation Optimization]

On the operational side, optimizing the energy use of MCS requires balancing supply and demand [117]. The work in [118] modelled the stochastic and dynamic behaviour of charging demand. This is to reduce operating costs while improving mobile charging service levels. Out of consideration for the benefits of MCSs, the work in [119] proposed an optimization on transport vehicle routing problem with time windows, which is optimized by MILP.

The maintenance of MCSs to complete grid line rehabilitation was considered in [120], with the dispatch of mobile battery-carried vehicles to stabilise the grid load. A recovery model for distribution systems based on MCSs is proposed. Ding et al. modelled it into a MILP optimization problem and solved it by an algorithm based on auxiliary induced functions. The work in [121] presented an energy trading system involving multiple MCSs and EVs. The system formulates the incentives between MCS and EV as an auction game, where MCSs act as the auctioneers and EVs act as the bidders. Experimental results demonstrate the fairness guarantee of the system for mobile charging. The work in [122] modelled MCSs as a queuing process. It developed mathematical models to characterize the placed MCSs, for minimizing operating costs and battery capacity of MCSs with efficient mobile charging services provided.

[MCS Scheduling]

In contrast to First In First Serve, an approach based on Nearest Job Next policy was proposed in [123]. Here, MCSs serve the next closest EV after the completion of the previous charging service. The work in [124] modelled MCSs path planning as a MILP problem, considering different possible service allocations and constrained operating range. This is to minimise the total distance travelled of transport vehicles. In order to increase the number of EVs that obtain charging services, the work in [125] applied an ILP to determine the optimal driving path of transport vehicles. For more accurate information, the work in [126] proposed a reservation-based intelligent scheduling scheme for efficient MCS utilisation. The proposed scheme is suitable for charging on demand with pre-charging reservation at MCSs. Nazari-Heris et al. proposed a smart parking self-scheduling model for EVs [127]. Here, MCSs are involved in the planning of energy production and storage in RES system, as interim BESs. The work in [127] aims to quantify the equity implications of MCS operation, the optimal siting of RES system.

2) In-motion EV Charging Decision: In-motion EV Charging can be regarded as V2V charging on-the-move, or accompanying charging. This convenient mobile charging mode has been in the spotlight in recent years as battery technology has evolved. Cisco Technologies also filing a patent for In-motion EV Charging in 2019 [128]. Table XIX compares related works in in-motion EV charging decision under mobile charging mode.

Table XIX. Literature Related to In-motion EV Charging Decision under Mobile Charging Service

Year	Ref.	Methods & Techniques	Objectives
2018	[129]	Hardware analysis	Improve charging stability
2021	[130]	Hardware analysis	Optimize the distribution of energy

The work in [129] investigated the technical aspects of in-motion EV charging and proposed a novel structure for V2V wireless charging technology to increase the possibilities of wireless charging services. In [130], EV fleets are used as a collaborative system where EVs in the fleet can share batteries with other EVs while driving to optimise the distribution of power across the EV fleet.

E. Gaps Between Academia and Applications

Real-world examples of mobile charging stations for EVs include a portable EV charger launched by a British technology firm, which caters to EV owners who cannot charge at home [131]. Portable charging stations, also known as charge points or Electric Vehicle Supply Equipment (EVSE), supply electrical power for EVs [132]. Power Sonic, a company providing mobile EV charging stations in the UK and France, has offered several portable charging systems to help EVs with temporary charging needs [133]. The concept of portable charging stations is well-defined in literature as a means to supply power for EVs on-the-go. These mobile charging solutions offer flexibility and convenience for EV drivers, especially in situations where traditional charging infrastructure is unavailable or limited.

However, this type of service is limited by the following issues:

- **Range & Capacity:** Portable Charging Stations (PCSs) have a limited capacity, which can limit their applications in areas with a high concentration of EVs [134]. The capacity of PCSs must be carefully planned to maximize their utilization. Berlin-based Chargery plans to use bicycles to deliver its 24kWh PCSss to customers, aiming to expand to 13 European cities and operate 350 trailers [135], to provide mobile charging supply to a certain extent.
- **Compatibility:** PCSs for EVs maybe incompatible with all EV models, while the charging rate and time can vary depending on the type of EV. This inevitably limits their utility and makes it difficult to provide a consistent charging experience [179]. Besides, companies may also want to consider choosing charging technologies that best meet customers needs [136]. Besides, companies may also want to consider choosing charging technologies that best meet customers' needs [134].

VI. Overview of Wireless Charging Service

Plug-in charging and V2V charging services present certain safety hazards, due to the presence of external charging equipment (e.g., charging cables, and converters). Therefore, the introduction of wireless charging service [137] aims to ensure the safety and convenience.

A. Introduction of Wireless Charging Service

Wireless charging converts electrical energy into a form of energy that can be transmitted wirelessly. Converters then receive energy (wirelessly) and convert it into electrical energy, enabling wireless EV charging. Wireless charging is a technology that enables the transfer of electrical energy without the need for physical cables or connections. It includes various methods including inductive and capacitive charging. Here, inductive charging, also known as contactless inductive charging, uses the principle of electromagnetic induction to transfer energy wirelessly.

In addition to inductive charging, another method of wireless charging for EVs is capacitive charging. Capacitive charging utilizes the principle of capacitive coupling, which enables the transfer of electrical energy between two objects without the need for physical connection. Capacitive charging involves the use of two plates, one on the ground and another on the underside of EV. When these two plates are in close proximity, electrical energy can be transferred wirelessly between them. Note that capacitive charging is still in the experimental phase, while more research is needed to optimize this technology for practical applications in EV charging.

With wireless charging technology, electric or dual-energy vehicles on the road can be quickly recharged using transmitters mounted on utility poles or other tall buildings [138]. Current wireless charging technologies include inductive coupling [139] and magnetic resonance coupling [140]. Both are efficient over medium distances and can be used to charge EVs wirelessly (as opposed to wired in the traditional plug-in charging mode) [141].

Fig. 17 demonstrates the wireless charging service. Depending on whether an EV is static during the wireless charging process, there are two main categories: Static Wireless Charging (SWC) and Dynamic Wireless Charging (DWC) modes. Under SWC mode, EVs park in user-friendly areas (e.g., supermarkets, parking lots) and perceive direct charging services via ground wireless charging assembly. Under DWC mode, EVs perceive charging service during driving through the road sections covered with an energy transfer loop.

B. Potential Risks of Wireless Charging Service

Wireless charging technology has rapid development in recent years and is being applied in some cities. Literature have

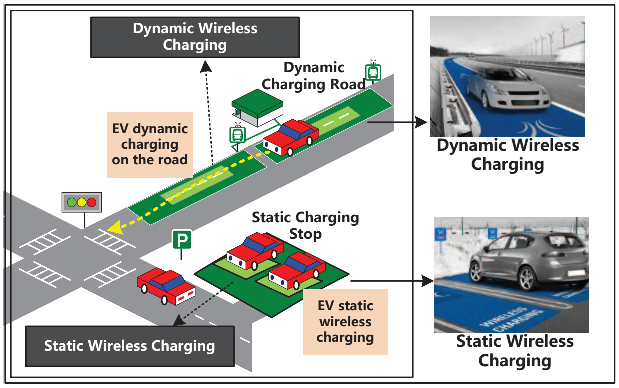


Fig. 17. Illustration of Wireless Charging Service

assessed the application prospects and significant economic benefits of wireless charging [142, 143]. However, there are still concerns about the mass adoption of wireless charging service.

Insufficient Charging: The low charging conversion rate is still the major gap for large-scale commercialization of wireless charging. Inherently, wireless charging is less efficient than traditional charging technologies, as there is a significant amount of energy loss in transition. Meanwhile, the wireless charging rate is still not fast enough, with most wireless charging powers below 11kW under wireless charging standards [144].

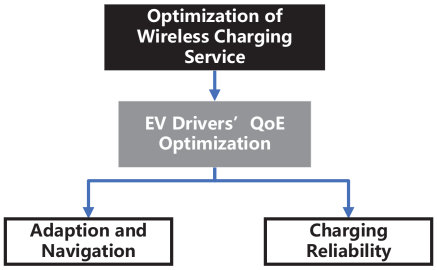
Safety Concerns: The safety of electromagnetic radiation is widely concerned. Firstly, electrical energy is transmitted in the form of electromagnetic waves. Here, metal obstacle detection between EVs and transmitters is mandatory, to avoid overheating and fire. Secondly, when a high-powered wireless charging device is in operation, it has an impact on the surrounding biological and electronic equipment. Therefore, how to alleviate people's concerns about health is crucial.

Road Renovation: Although DWC can effectively extend the driving range of EVs, it requires the modification of roads for pilot operation, a large upfront cost investment and human resource extensive cost on maintenance if applied for large-scale operation.

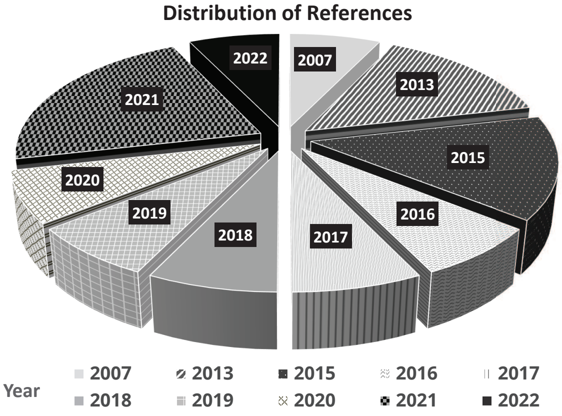
C. *Benefits of Wireless Charging Service*

The wireless charging service avoids the involvement of wired devices during the charging process, and therefore guarantees a relatively close and safe system. From EV driver's perspective, the wireless charging service allows EVs to charge on-the-move, saving the time EVs need to drive exclusively towards fix charging infrastructure. With two minutes of waiting time at each stop and 20 minutes at the terminal, the electric bus could gain one hour of wireless charging time. This can effectively extend the range of buses. From the security protection perspective, wireless charging does not require an external wired device, and therefore avoids security threats (e.g., illegal access at the software level) during the wireless connection.

Fig. 18(a) shows the optimization category under wireless charging service, while Fig. 18(b) shows the literature year on wireless charging service optimization. In the following review of this section, we focus on **EV Drivers' QoE Optimization** for the client's angle.



(a) Optimization Category under Wireless Charging Service



(b) Literature under Different Year

Fig. 18. Overview of Wireless Charging Service Optimization

D. *EV Drivers' QoE Optimization*

The previous mobile charging service focused on optimization at the operational level. In contrast, QoE for EV drivers is a key optimization target for wireless charging service. Table XX compares related works in Adaptation and Navigation under wireless charging mode. The following therefore addresses wireless charging optimization from a driver charging service perspective.

Table XX. Literature Related to Adaptation and Navigation under Wireless Charging Service

Year	Ref.	Methods & Techniques	Objectives
2018	[145]	Hardware analysis	Improve the efficiency of electricity transmission
2021	[146]	Data mining; Communication control	Improve EV driving range
2021	[147]	Mixed integer non linear programming	Relieve peak charging pressure; Extend EV travelling distance
2021	[142]	Dynamic programming; Fatigue model	Reduce EV battery size; Improve EV driving range

1) Adaptation and Navigation: Table XX compares related works in charging reliability under wireless charging mode. The SWC technology is applied when EVs are parked. This technology is of potential for applications in parking lots, supermarkets and residential areas.

Recently, the power and efficiency of SWC is increasing as technology advances, manufacturers (like Audi [148], Qualcomm [149], etc.) are already able to achieve stable SWC for commercial applications. Meanwhile, SWC for electric buses staying at stops is currently being implemented in public transport systems in Barcelona [150]. Here, dynamic charging and driving can be processed simultaneously, which eliminates the charging waiting time and helps to reduce range anxiety for EV drivers [145].

Under DWC mode, how to facilitate the deployed wireless charging road sections for path planning is of importance. In addition, the communication between the road and EVs is crucial for bridging the seamless and optimal energy transfer. Here, when an EV enters a dynamic wireless road segment, the EV should be informed so that the EV could slow down in order to obtain sufficient charging time [146]. An online coordination strategy was proposed in [147]. This work allows EVs to maximise the use of a dynamic wireless road, thus achieving grid load balance and maximising charging capacity. Meanwhile, DWC has commercial benefits for EVs, where battery costs can be significantly reduced when wireless road segments are large-scaled [142].

Table XXI. Literature Related to Charging Reliability under Wireless Charging Service

Year	Ref.	Methods & Techniques	Objectives
2017	[151]	Multi-objective optimization	Improve EV driving range; Maintain load balance
2015	[152]	Hardware analysis	Reduce the range anxiety; Increase charging opportunities
2013	[153]	Dynamic programming	Increase charging power; Maintain load balance

2) Charging Reliability: Table XXI compares related works in charging reliability under wireless charging service. SWC does not require substantial human involvement during charging service, and avoids some of the potential safety issues, such as the danger of electric shock in plug-in charging service [152]. The work in [151] controlled the wireless charging rate to balance energy supply, and demand to facilitate the integration of SWC with the grid. In contrast to SWC, DWC allows EVs to charge while they are on-the-move [153]. Under DWC mode, charging panels are laid on the road, for EVs charging while on-the-move. This provides continuous energy transfer to EVs, without much concern for the capacity of batteries.

E. Gaps Between Academia and Applications

Wireless charging for EVs has seen real-world implementation in various cases. One such example is a pilot project in Sweden, where a 1.6 km road segment was transformed into a wireless energy charging dock. Stellantis, the parent company of popular car brands like Chrysler, Citroen, and Peugeot, also demonstrated dynamic wireless charging by driving an electric Fiat 500e on a 1.05 km circuit in Italy [154]. Several technological advancements have also been made in the wireless charging sector for EVs by companies in Italy [155]. These real-world applications and technological developments highlight the potential of wireless charging to offer convenient and efficient EV charging solutions.

However, this type of service is limited by the following issues:

- **Infrastructure Deployment:** The implementation of wireless charging infrastructure requires a significant amount of investment in both hardware and software [156]. This includes the development of conductive and contactless charging infrastructure [156], as well as the establishment of minimum standards and requirements for EV projects [157]. Companies like Siemens are investing millions of dollars in wireless charging technology [158].
- **Standardization:** Currently, the lack of agreed-upon standards for wireless charging technology makes it challenging to ensure that wireless charging infrastructure is available for all EVs, and limits the availability of wireless charging stations [26]. Notably, SAE recently developed the first global standard for wireless power transfer for EVs and EVSE [159]. The standard, known as SAE J2954, enables light-duty EVs and infrastructure to safely charge up to 11kW across a 10-inch (250 mm) air gap, achieving efficiencies up to 94%.

VII. DISCUSSION ON OPTIMIZATION METHODS TO SERVICE MARKETS

A. Layout of Mainstream Optimization Methods in Literature

Given review in Sections II, III, IV, V and VI with angle of service operator and client, Fig. 19 illustrates the methods that are widely applied in literature.

Basically, the “Mathematics and Operational Research” was extensively studied in literature, with heuristic and theoretical optimization as well as operation research methods mainly characterized. The “Incentive Mechanism” as another way for service optimization, to motivate and encourage the engagement of service operators and clients. In recent years, “AI and ML” have received great attention thanks to the rapid development of computation capability and fruitful data collected through service operation.

Inherently, the “Mathematics and Operational Research” is mainly used to solve the multi-objectives problem (e.g., demand regulation, route planning, charging behavior shaping and price etc). “Incentive Mechanism”, alternatively pushes both service operators and clients beyond their limits, particularly been studied for V2V charging service. Here, game algorithms such as oligopoly game and Gale-Shapely algorithm are often used in V2V matching, to optimize the charging service. Emerging “AL and ML” reduce the time required to solve complex problems and thus increase the efficiency in the applied area, with continuous data learnt from E-Mobility service to gear the revolution of expert knowledge.

B. Plug-in Charging Service Business

Based on the International Energy Agency prediction, the total number of global EVs will exceed 130 million by 2030 [160]. The development of charging infrastructure market

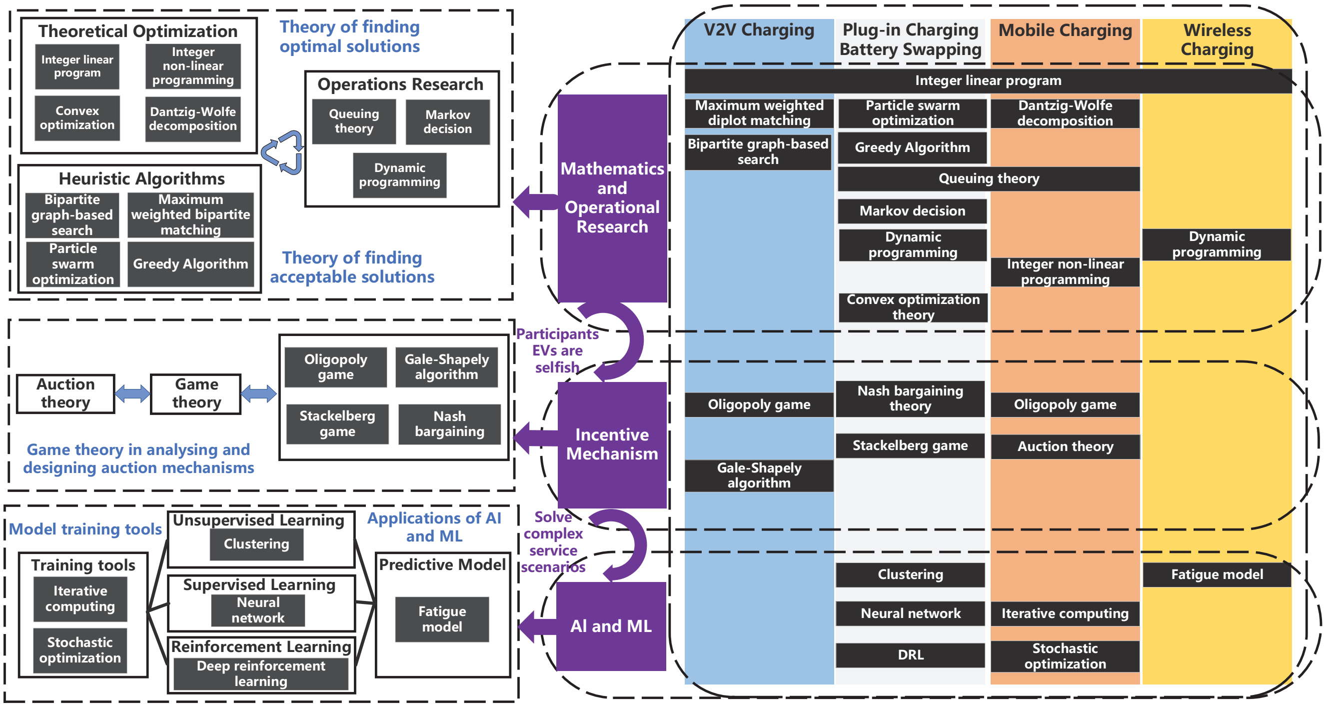


Fig. 19. Logic Relationship across Optimization Methods

plays an important role in promoting EV popularization. The construction and operation of charging infrastructure is implemented by different market actors, including public or semi-state enterprises, as well as private companies [161].

Besides, the business models of charging infrastructure market involve manufacturing, installation/development, network operation and sales & marketing [162]. Some companies, such as ChargePoint and SemaConnect devote to installing and operation a network of CSs [163]. However, these companies do not retain the ownership of CSs. Different from above companies, Telsa, EVGo and Blink Network operate in an integrated service function, including sizing CSs, owning charging infrastructures, supplying charging service, managing network access and collecting revenues [163].

C. Battery Swapping Service Business

As for battery swapping service mode, the Better Place Company has first launched the business mode and Tesla has also attempted to operation in this way [53]. However, they are both failed due to huge hardware expense and meager profits. Fortunately, benefiting from the rapid development of battery and amount of EV, Chinese automakers NIO and BIAC have successfully promoted this energy supplement mode for private EV drivers in China. Besides, as a battery swapping service operator, Alton has also verified the profitability of battery swapping business mode [55]. Since China is the largest EV market in the world and the government persistently promotes the convenience of energy supplement, the battery swapping service mode has great market potential and prospective future [164].

D. V2V Charging Service Business

The V2V charging technology has emerged as a promising solution to tackle the challenge of limited charging infrastructures for EVs. The V2V charging enables EVs to share their battery power and provide charging services in P2P manner, especially in areas where charging infrastructures are scarce or absent [165]. With the increasing adoption of EVs and demand for more convenient and accessible charging options, the market potential for V2V charging technology is significant. Moreover, V2V charging can also enhance the connectivity and inter-operability of EVs, further promoting their usage and adoption. While there are still technological and regulatory challenges to be addressed, the V2V charging is a promising technology that has a bright future in EV market.

E. Mobile Charging Service Business

Mobile charging of EVs is a promising technology that can provide convenient and efficient charging solutions for EV owners. The global market for portable EV charging devices is expected to expand due to the rising demand for EVs and growing environmental concerns [166]. To successfully market mobile charging, companies need to focus on educating consumers about the benefits of portable charging, such as convenience, flexibility, and accessibility. There is also need to address consumer concerns about the cost and compatibility of portable charging solutions.

F. Wireless Charging Service Business

Wireless charging is a promising technology that can revolutionize the EV charging industry. The global wireless EV charging market is expected to grow for 46.8% from 2022 to 2029, reaching a value of $ 506.58 million [167]. The market is driven by factors such as the increasing demand for EVs, the need for convenient and efficient charging solutions, and the growing focus on reducing carbon emissions. However, the market also faces challenges such as the high cost of wireless charging infrastructures, inter-operability issues, and the need for standardization.

VIII. FUTURE DIRECTIONS

A. Integration of Multi-energy in EV Charging

As the electricity generation still relies heavily on thermal power, there is currently controversy over the level of carbon emissions from EVs. Thus, optimizing EV charging therefore requires consideration of the renewable energy sources.

The utilization of PV system for EV charging is popular recently. However, PV system still requires high upfront deployment cost. In addition, considering the practical charging scenarios, plenty of EVs request charging services during night period (e.g., in residential areas), the timing of energy generation and charging makes PV charging system more inconvenient. Also, there is considerable wind power capacity worldwide, but relatively few applications applies wind power as a source for EV energy. This is because wind power does not provide a steady supply of electricity, thus cannot meet the large number of EV charging requests.

Besides, hydrogen fuel cells has been considered as promising alternative energy source for automotive, with potential to become an important part of future energy landscape [168], [169]. It is highlighted that reliable hydrogen supply systems and exploration of new applications are important for the success of hydrogen energy adoption [170], [171].

B. Concern on Cyber Security

The rapid development of intelligent vehicles have promoted the vehicle market. However, this also exposes the vehicle system to the open network environment, and may be threatened by potential network attacks. The in-vehicle system faces risk of cyber attacks, and it may be attacked by hackers causing serious threats to society. This is due to that the number and types of external interfaces of vehicles have increased rapidly. Accordingly, utilizing existing vulnerabilities of software and system, hackers can attack the in-vehicle system for the purpose of in-vehicle information theft, driving system failure, remote control of braking system etc. Therefore, the cyber security of in-vehicle system requires substantial concern.

Apart from above, the security of Vehicle-to-Everything (V2X) communication is another focus. If the attacker always sends fake messages, the EV would be disturbed to ignore various warnings from cloud controller, causing unreasonable decision-making behaviors. Besides, privacy protection is an important field of V2X communication. When a message containing personal information is sent from EVs, it is easy to be track and cause a serious privacy problem for the driver.

C. Application of AI

The AI technology has been regarded as one of the most important technological innovation in recent years. It has changed almost every aspect of life and industrial production. Considering the rapid development of EV market, the application of AI will revolutionize intelligence of EVs. As for EV drivers, benefiting from deep neural networks and big data, AI can analyze the daily charging behaviors and preferences, achieving a personalized service recommendation. Besides, based on computer vision and parallel computing algorithms, AI has significantly improved the performance of intelligent vehicles in self-driving. As for the power grid, AI can analyze real-time load and provide dynamic pricing for EV drivers. Through adjusting charging demand, the steady and reliable operation of power grid can be achieved. Moreover, utilizing data form traffic flow, population density and forecasted EV adoption rates, AI can help charging operator to find the optimal location selection and charging infrastructures planning.

D. Promotion of Global Policy

Given the increasing attention from worldwide, there is necessity to design the top-level policy and accelerate technology innovation. Firstly, the energy generator sectors is realized based on the green energy supply, and sequentially the energy consumption of EVs is promoted through clean energy. In the light of this, it is necessary to continuously regulate the energy structure under the governing of policy. Secondly, policy for accelerating EV adoption should be strengthened and synchronized among world. Thirdly, accelerating the application of emerging technologies such as V2X, 5G, AI etc, is with potential to realize the ubiquitous information sharing and fusion, so as for optimized decision making on E-Mobility service. Therefore, standardization of these into regulation of E-Mobility ecosystem should be positioned on the pathway.

IX. CONCLUSION

In the future, technologies of transportation electrification will accelerate to achieve carbon neutrality. Starting with the vision, the importance, challenges, holistic view on linking typical E-Mobility services are presented. This paper introduced overview of plug-in charging, battery swapping, vehicle to vehicle charging, mobile and wireless charging for service optimization, from the angle of service operators and clients. Further to literature review, this paper identified the gap between academia and industry application to promote the technology transformation, with recent optimization methods-to-market efforts been showcased. In the end, this paper was concluded with several future direction highlights on integration of multi-energy systems with EV charging, concern on cyber security, application of AI and promotion of global policy. It is expected that E-Mobility can make an important contribution to carbon neutrality worldwide, contribute to environmental friendly society and future city.

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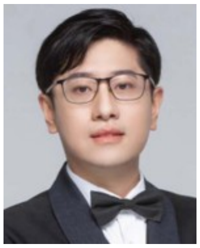

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