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COORDINATED OPERATION OF BATTERY SWAPPING AND CHARGING STATIONS FOR ELECTRIC VEHICLES: A REVIEW

Sachin S. Kumbhar[a, b, *], Vaiju N. Kalkhambkar[b]

[a] *Shivaji University Kolhapur, School of Engineering and Technology, Department of Technology, 416004 Maharashtra, India*

[b] *Kasegaon Education Society's Rajarambapu Institute of Technology, Department of Electrical Engineering, Sakharale, 415409 Maharashtra, India*

[*] corresponding author: `sachin.kumbhar@ritindia.edu`

Abstract. Over the past decades, the number of electric vehicles (EVs) has grown rapidly due to advances in EV technologies, charging infrastructure, public charging services, and improvements in battery materials. The governments in many countries have implemented policies to prohibit fossil fuels and reduce greenhouse gas emissions. Nevertheless, EVs require longer charging times than refueling at gasoline stations because of charger limitations and battery characteristics, which hampers the promotion of EVs. Consequently, batteries can be swapped with fully charged ones within a few minutes at Battery Swapping Stations (BSS) similar to existing gasoline stations. However, Charging Stations (CS) are required to charge the batteries in EVs due to a lack of swapping facilities and individual constraints. Recently, researchers have examined the Battery Swapping and Charging Stations (BSCS) approach by proposing optimization methods, operational models for BSS and CS service operators, and implementations of BSS and CS at private and commercial locations. This study provides a comprehensive review of the key challenges associated with BSS and CS, including optimal location selection, coordination, charging infrastructure, charging strategies, feasibility, battery ownership models, grid integration, and battery management. Also, this article identifies key research gaps and future directions, emphasizing the need for technological innovations. It also provides integrated solutions to overcome these challenges and enhance the overall efficiency of EV infrastructure.

Keywords: Electric vehicle, battery swapping station, charging station, battery swapping and charging station.

1. Introduction

EVs have tremendous potential to provide additional services across different domains. The electrical power system is one such domain, and with vehicle-to-grid (V2G) operation, frequency regulation can be achieved [1]. In addition, the supply voltage can be stabilized [2], and renewable energy can be integrated into the power system [3, 4]. EVs require frequent battery charging to achieve long distances; therefore, many researchers have studied charging control strategies for EVs [5–7]. The battery charging time depends on the battery type and the capacity of the EV. Typically, charging times vary between 4–8 hours, and with this charging, an EV can travel 80–200 km. To achieve longer distances with an EV, the required travel time increases due to both driving distance and charging time. Research has been carried out on wireless charging stations for EVs to increase the traveling range [8, 9]. Increasing the number of charging stations (CS) in different locations can extend travel range, but total travel time remains high because of the required battery charging time. EVs can be charged based on time and electricity price, so a more constant load on the system can be achieved. Fast charging stations are entering the market to charge EVs; however, charging times remain longer than refueling internal combustion (IC) engines. Current research on battery swapping and charging stations (BSCS) is ongoing, and the areas are listed as shown in Figure 1: integration of BSCS; charging infrastructure; energy management in BSCS; integration of BSCS into the smart grid and renewable sources; optimal location of BSCS considering road and transportation networks; charging strategies for BSCS; battery ownership from owners' and customers' points of view; and the feasibility of BSCS in the EV market.

The importance of EV charging infrastructure focuses on behavior across different scales, vehicle performance, driving patterns, power-system demand, and interactions between technologies [10]. EVs offer significant benefits, including reduced dependence on fossil fuels, improved safety, economic savings, lower noise, zero emissions, and low maintenance [11–16]. Technological developments in the EV industry are increasing day by day; however, stakeholder concerns about innovative concepts should be considered when making investment decisions at the planning stage [17, 18]. Social difficulties may arise for existing EV owners due to utility-grid constraints, limited availability of recharging stations, and most importantly range-anxiety issues [18–24]. The profitability of EV charging stations

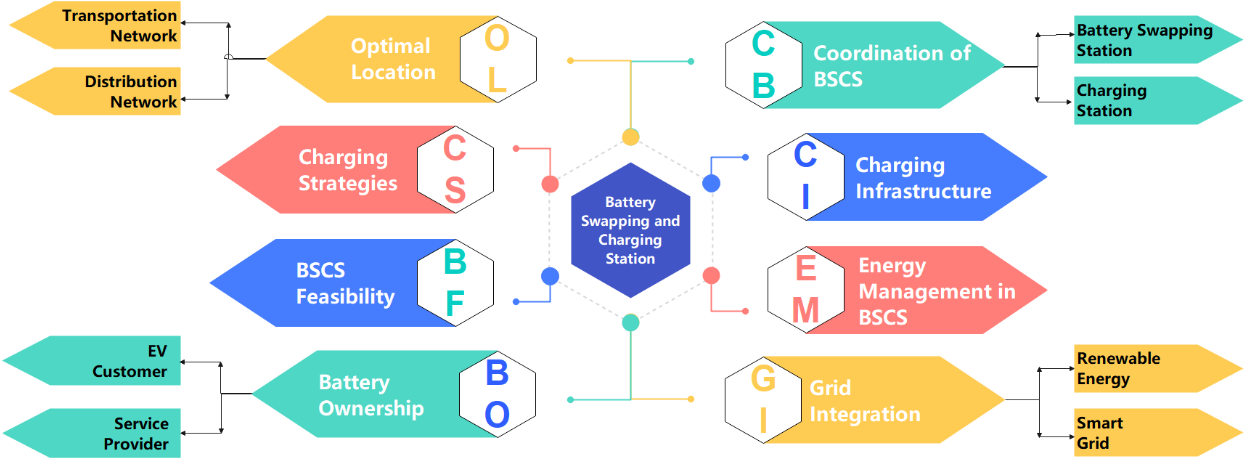

Figure 1. Different technical challenges of battery swapping and charging station technology.

can be maximized by addressing location challenges such as locating stations near selected bus stops [25]. Using an operational planning framework, centralized charging stations (CCS) provide maintenance and convenient charging platforms for delivery services and EV battery charging [26]. Economic development and technological progress have driven electrification since the Industrial Revolution, and electrification now extends deeper into the energy transition across transportation, industry, and buildings toward a zero-carbon economy for climate mitigation [27]. Retired electric vehicle batteries (REVB) can cause environmental pollution if not handled properly, yet economic benefits in electricity markets can be enhanced by deploying REVB in various market applications [28]. As EV batteries eventually retire after use, rigorous research and integrated waste management are required [29]. Optimal charging strategies can meet deadlines while accounting for financial profit [30]. Under dynamic electricity pricing, smart charging stations can execute charging tasks economically, providing aggregators greater flexibility and enabling coordinated energy sharing among batteries. Charging batteries in charging stations takes more time, so the battery swapping technique is used along with a dynamic operational model in the electricity market [31].

Battery swapping is a suitable solution for charging batteries in the minimum time. Swapping EV batteries provides key benefits, such as very fast recharging of EVs compared with conductive charging. A bus driver needs to drive the EV to a BSS, park in the designated area, and the battery is swapped effortlessly using an autonomous system [32]. The investment in a battery swapping station can be recovered more quickly by integrating BSSs with renewable energy sources [33]. Plug-in Hybrid Electric Vehicles (PHEVs) and Plug-in Electric Vehicles (PEVs) battery swapping technology is a remarkable alternative. Wireless charging, along with battery swapping and remote assistance for home robots, has also been examined [34]. Many researchers have worked on BSSs; however, EV charging has not been completely ruled out, so there is a need for both charging and battery-swapping stations [35].

Type of Charger	Year	Ref.
First public DC charging station	1914	[36]
Level 1 AC charger	1991	[37]
Level 2 AC charger	1996	[38]
Level 3 (DC fast charging)	2009	[39]
Tesla supercharger network	2012	[40]
Tesla battery-swap	2013	[41]

Table 1. Evaluation of charging station improvements.

The BSS is more convenient for public transport, like buses, as well as private EV owners. Some customers rely on the charging system and charge EVs at charging stations. Therefore, interconnected BSS and CS need to be developed. With the BSS and CS, the time required for an EV owner to charge the battery is reduced significantly. The evolution of charging station improvements is given in Table 1.

1.1. METHODOLOGY

A structured approach based on a review strategy is adopted to ensure a broad and systematic review of the literature about BSCS coordination. The following steps outline the methodology used in this manuscript:

(1.) **Literature Exploration Approach:** A literature search is conducted across multiple academic databases, including IEEE Xplore, ScienceDirect, SpringerLink, Scopus, and Google Scholar. The search was limited to peer-reviewed journal articles, conference papers, high-impact reviews, online data, and websites published between the last 27 years (i.e 1998 to 2025). Primary keywords included combinations of the following terms: “Battery swapping station”, “Charging infrastructure for electric vehicles”, “Optimal location of EV stations”, “Grid integration of EV charging”, “Battery degradation in EVs”, and “Renewable energy and EV charging”.

(2.) **Contents Inclusion and Exclusion Criteria:** The content is selected based on its relevance to the review scope. The criteria for content selection is as follows:

(a) Inclusion Criteria: The studies presenting models, simulations, and case studies of BSCS systems are considered. Articles addressing optimal placement, energy management, charging strategies, battery health in EV infrastructure, integrating renewable energy or discussing their grid impact, and BSCS are also included in the proposed study.

(b) Exclusion Criteria: The excluded papers focusing solely on battery chemistry or materials without application to swapping or charging systems, battery management systems, and publications without experimental data or clear methodology. This filtering helped maintain a focused and evidence-based foundation for this review article.

Each paper was analyzed for methods used, key findings, data sources, and limitations. Cross-comparisons were conducted to identify trends, gaps, and emerging directions in BSCS research. The major contributions of this review paper, along with challenges, are briefly highlighted as follows:

In these review articles, various techniques of BSCSs, coordination of BSS and CS, along with the requirement considering the effective usages of grid energy, locations of BSCS for increasing range of EVs, and charging strategies for BSCS are taken into account. Not only are grid integration and energy management reviewed, but also the effect of battery life during charging is described with various challenges and opportunities. Areas like BSCS architecture, battery swapping techniques, charging strategies, and scheduling are considered in this article. Various problems, optimization techniques, challenges, and future scope for the BSCS are discussed in every section.

2. Coordination of BSS and CS

In the electricity network, BSCS provides electric vehicle refueling services. Coordinated operation of BSS offers an excellent opportunity to lower operational costs and maximize system flexibility [42]. Moreover, operating costs are minimized by the cooperative operation of BSCS, the microgrid, and groups of residential buildings. Economic operational flexibility and profitability can be enhanced by using used electric-vehicle batteries as Retired Battery Energy Storage Systems (RBESSs) at the BSCS [43]. The locations of charging and BSS can be identified by considering the social ability of users. Such layouts of charging and battery swapping-station locations can minimize EV electricity consumption and maximize users' satisfaction in urban cities [44]. One promising complementary energy solution is to interconnect charging stations with battery swapping to meet the growing EV demand. A framework for BSS with a local charging mode is developed by proposing a network model in [45]. In many cases, batteries can be dispatched between BSCS for efficient operation and profit maximization. The factors, such as parking spaces, battery requirements, charging stations, and swapping stations, are considered when interconnecting BSCS [46].

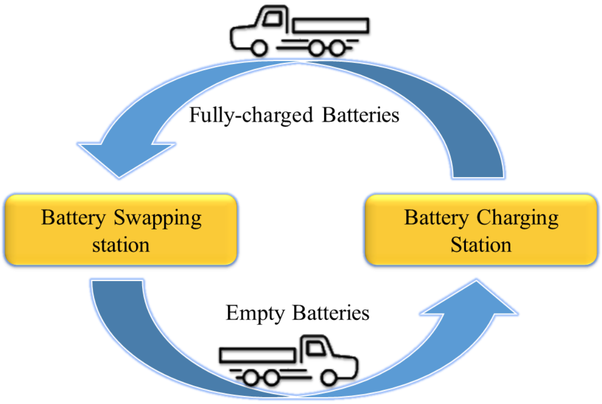

Figure 2. Battery transportation between swapping and a battery charging station.

A Mixed Queuing Network (MQN) model is presented to consider various factors and to study the impact of parameters on BSCS. In many cases, batteries need to be transferred to BSS because the battery charging stations are located away from the BSS. Therefore, the batteries charged at battery charging stations (BCS) can be transferred to the BSS, as shown in Figure 2 [47]. A two-dimensional battery dispatch model can be helpful in solving such problems. This system can reduce transportation costs associated with transferring batteries between BCS and BSS. It also contributes to the power system network, but this research is still in the early stages. A mobile battery swapping service can be used similarly [48]. A mobile battery swapping service app is used by the battery swapping service management system to transfer batteries between BCS and BSS.

EVs such as buses and taxis may also impact the service capacities and earnings of battery swapping and charging stations. A scholastic model is proposed to maximize the benefit for the vehicle operator and the Electric Vehicle Supply Equipment (EVSE) service provider [49]. Factors such as vehicle speed, price of the swapping service, service capacity, vehicle battery size, and charging-station power are also investigated. Automated BSCS have been designed and developed not only for EVs but also for Multirotor Aerial Vehicles (MAVs) [50]. These stations are required for MAVs because of their short flight times and the associated charging time. Accordingly, many researchers have proposed planning for BSS for EVs and electric flights, and separate planning for EV charging stations. Considering this scenario, some researchers have proposed integrating battery swapping with charging stations to maximize the profits of vehicle owners and service providers. The overall block diagram of the BSCS is shown in Figure 3.

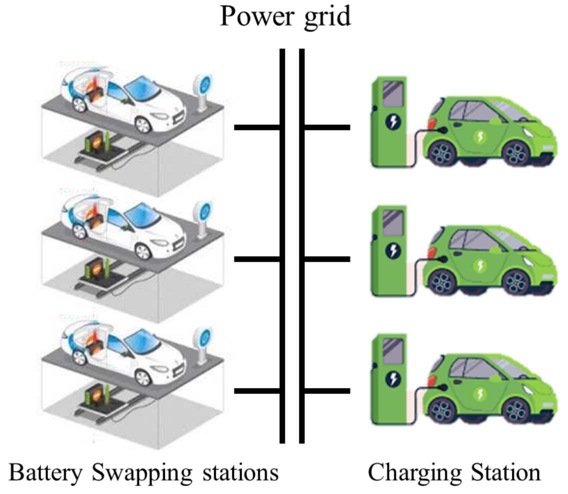

Figure 3. Battery Swapping Station along with Charging Station.

Many charging stations have already been installed in the market. Nowadays, the number of BSS is increasing in the market as technology is moving towards battery swapping. BSS needs to coordinate with CS to increase the profit of both BSS and CS. In this coordinated BSS framework, energy can be transferred towards the battery swapping stations and vice versa. As energy can be stored in BSS and EVs recharged in CS, the load on the grid can be minimized. Considering such scenarios, researchers may develop coordinated BSS and CS, or BSCS.

3. Optimal location for BSCS

Currently, EVs are widely used because of their overall contribution to the energy sector and in reducing CO_2 emissions [51]. EVs require a battery storage unit to store energy, which is later converted into mechanical energy during operation [52]. Sometimes EV owners need more time to charge because they must wait in line until an occupied charging station becomes available. Some EVs with a 50 kW charging plug require nearly 2 hours with fast charging, and a normal charging station with a 7 kW charging plug requires nearly 4 to 13 hours [53]. Recently, BSS has entered in the market, where discharged batteries from EVs can be replaced by charged batteries [54, 55]. In 2013, Tesla Motors Company demonstrated battery-swapping technology that can take only approximately 80–90 seconds to exchange a discharged battery with a charged one [56]. Meanwhile, different techniques have been developed to swap batteries for public transport [57].

The electricity price is estimated using historical data from BSS and electrical demand [58]. Increasing the profit of BSS is essential, so the stations need to know when to charge batteries and the best location for BSS. For charging the batteries, a novel centralized optimal model is proposed based on the charging strategy of EVs, including electricity price and using a radial distribution system, an optimal charging station location is determined [59]. Also, optimal charging station locations, along with the optimal charging priority of EVs, were developed using a heuristic algorithm [60]. Additionally, the infrastructure planning process for the BSS location was developed with a robust model that includes planning strategies and the impact of batteries [61]. Furthermore, operating charging station models were proposed to study the electricity price along with the demand for batteries [62]. To assign proper charging scheduling of BSS and to reduce the operational cost under electricity prices, an optimal model was developed by Wu [63].

The sizing and location of BSS were addressed by formulating a mixed-integer, nonlinear, and nonconvex programming model [64]. Problems related to charging scheduling for reducing the price by matching the demand have been solved using a generalized Benders decomposition-based algorithm [65]. A suitable charging station location for the EV is obtained by checking the battery status as well as the geographical location of the EV using centralized and distributed methods [66]. The profit of the BSS can be increased by considering optimal charging and discharging cycles [67]. Focusing on urban electric taxis, an optimized BSS scheme is proposed [68]. For short-range flights, scheduling of charging stations and battery swapping is proposed [69]. The location planning of CS and BSS takes into account the behavioral capabilities of the users [44]. Table 2 shows the optimal location identification by considering the transportation network and distribution network for the BSCSs.

However, facilities with a single type of BSS or charging pile are not convenient for rapid charging and for minimizing power supply and demand for EVs. Therefore, to minimize this problem, a joint planning method for Charging Battery Swapping Stations (CBSSs) and charging piles is proposed [70]. The Power System Network (PSN) and the Road Transportation Network (RTN) are used for optimal placement of BSCSs [71]. Various constraints, such as the layout of charging piles and geographical locations, are considered for joint planning. In addition, the battery-swapping demands of Private Electric Vehicles (PEVs) and Taxi Electric Vehicles (TEVs) are also considered. The optimal locations can be identified for the CBSSs by considering different scenarios to reduce travel time while accommodating longer travel distances for EVs. Better optimal location results can be obtained by considering a bi-level (traffic and distribution system) approach along with renewable energy. Along with these constraints of public transport data, the energy required to charge EVs, and geographical locations, the maximum range and service can be achieved. This will help increase the range of private EVs and public transport, and also reduce the overall overloading of the power network.

Ref.	Battery swapping station	Charging station	Transportation network	Distribution network	Optimization model
[54]	Y	Y	N	N	Improved differential evolutional algorithm combing with Monte Carlo searching (IDEA-MCS)
[59]	N	Y	N	Y	Artificial Bee Colony (ABC) algorithm
[60]	Y	N	Y	N	Particle Swarm Optimization and Genetic Algorithm
[64]	Y	Y	N	N	Modified differential evolution algorithm
[65]	Y	Y	N	Y	Generalized benders decomposition algorithm
[44]	Y	Y	N	N	YALMIP/CPLEX
[70]	Y	Y	Y	Y	Monte Carlo simulation method
[71]	Y	N	Y	Y	Bi-level optimization model

Table 2. Optimal location of BSCS.

4. Charging strategy for BSCS

A number of measures have been taken to address the problem of charging management [72–74]. The most important challenge is determining when and whether to charge the EV. Generally, EVs can be charged when they are parked at homes or at the charging stations; in this situation, electric vehicles are considered as a static load [75]. Recent research efforts increasingly focus on where EVs are moving in the road network with considering the nature of EVs. Mainly, when to charge an EV is a serious concern in E-mobility [74–76]. In that case, EVs should be purposefully guided toward the appropriate charging station during their ride, considering the waiting time in line for the charging facility [77, 78]. To minimize the gathering of EVs at CS, making reservations well in advance is recommended [79–81]. These reservations are specified by a specific time and specific charging stations. High charging rates strongly influence battery degradation and, therefore, a proper charging strategy can improve the performance of the battery [82].

Battery degradation and longer charging time are key challenges in charging technologies and there is a need for alternative methods for charging EVs. Plug-in charging solutions have shown success with fast charging, achieving a full charge in approximately 30 minutes for an EV [83]. However, this accelerates battery degradation, so battery swapping is the most cost-effective option for two-wheelers, taxis, buses, and e-bicycles [84]. In this regard, battery-swap technology has been considered along with distributed charging management [85], taking into account drivers' preferences and traffic congestion. To improve consumer satisfaction, BSCS has been developed with attention to consumers' range and loss anxiety [86]. By eliminating the battery from the EV, the vehicle cost can be minimized. In this model, a third party can own the battery and provide a fully charged unit in exchange for the discharged battery [87]. From both power-system and customer perspectives, charging stations can generate profit by analyzing day-ahead battery demand. Also, in BSS, batteries are depleted from operation and enable the matching of reusable solutions for these batteries [62]. In addition, optimizing charging and discharging cycles and minimizing economic loss are considered to reduce battery degradation.

Scheduling of the batteries depleted from EVs depends on voltage, power loss, charging cost, as well as the price of battery swapping. Along with these considerations, a spot pricing-based centralized charging strategy is proposed [60]. Considering the inventory of fully charged batteries, a charging-scheduling method for the charging bays was proposed to minimize the charging cost, including battery degradation cost [88]. Considering the arrival rate of incoming EVs for charging and maximizing the profit of the BSS, the Optimal Battery Charging Algorithm (OBCA) was proposed [68]. The charging strategies for BSCS, considering road and distribution networks, are provided in Table 3.

BSCS is a promising solution for charging EVs and providing improved swapping and charging services. Optimal operation can be achieved by integrating BSCS with a closed-loop supply chain (CLSC), in which batteries are charged at the BCS and subsequently delivered to the BSS via the battery logistics system. Ancillary services, such as load regulation and spinning reserves, are coordinated between the wholesale electricity market and the BCSs. The logistics system can deliver batteries between the charging station and the CLSC, as shown in Figure 4 [89].

The profit of a BSCS can be increased by managing both power and data. Access to data from a large number of EVs within the smart grid framework improves the management of V2G and G2V. The electricity market price and the performance of individual customers

Ref.	Battery swapping station	Charging station	Transportation network	Distribution network	Optimization model
[86]	Y	Y	Y	N	Linear integer programming model under deterministic and fuzzy scenarios
[60]	Y	N	N	Y	Particle swarm optimization and genetic algorithm
[88]	Y	N	Y	N	Battery heterogeneity-based swapping service framework
[68]	Y	N	N	N	Linear programming
[89]	Y	Y	Y	N	Mixed-integer linear programming

TABLE 3. Charging strategy for BSCS.

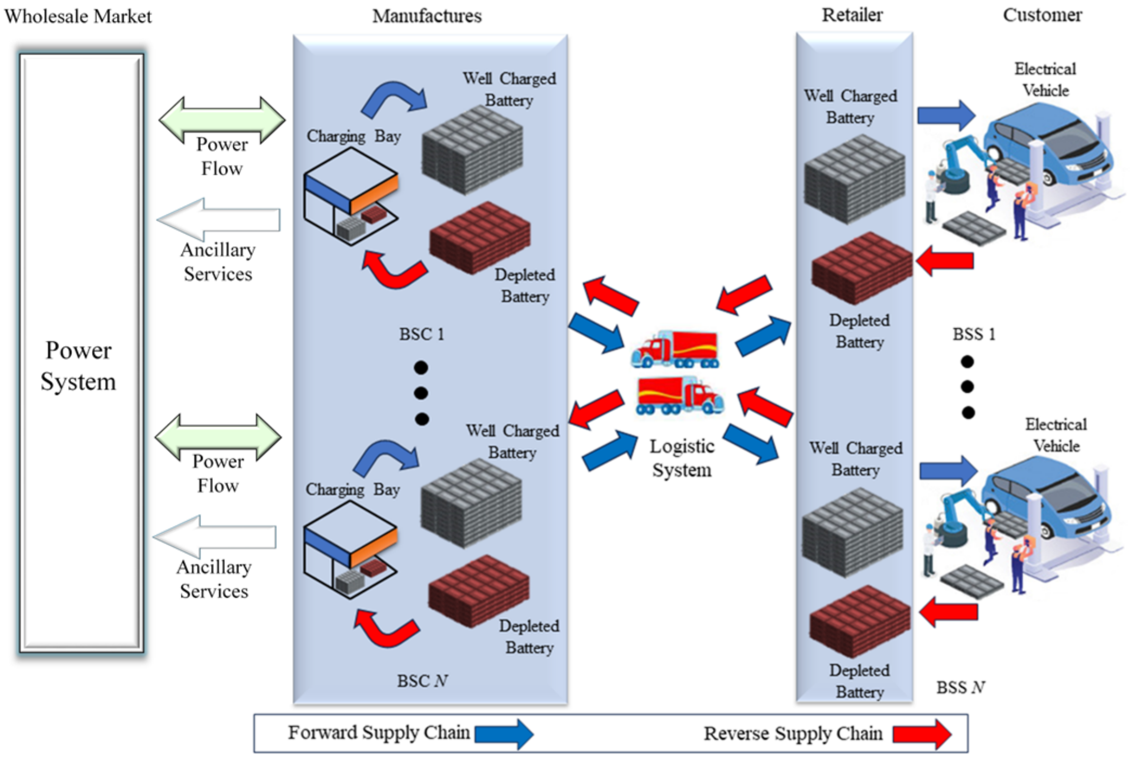

FIGURE 4. CLSC based battery swapping and charging system.

can be maintained by considering V2G. Network congestion and energy losses can be minimized in a BSCS by developing smart charging strategies. In addition, participating in various auxiliary services can increase profit. To maximize profit, batteries in the BSCS can be discharged to the grid by developing appropriate strategies and considering constraints such as peak load periods, renewable energy sources, parking time, traveling time, and battery degradation.

5. GRID INTEGRATION WITH BSCS

The EV charging fleet management is a unique field as compared to other advanced transport sectors, and it includes data management as well as power management. Leveraging power-flow analysis and information and communication systems, the charging infrastructure can be integrated with the utility grid to reduce charging costs [93–95]. Access to a large number of EVs requires a framework aligned with Smart Grid (SG) applications to improve the management of vehicle-to-grid (V2G) and grid-to-vehicle (G2V). Within this structure, an EV aggregator serves as an intermediary between individual EVs that provide flexibility for the electricity market and the independent system operator (ISO). EV aggregators face uncertainties in V2G management due to price volatility in the electricity market and the combined stochastic performance of individual customers [96, 97]. Financial risks to EV aggregators arise from outages of power system components and large-scale integration of renewable energy resources.

Several studies have examined the integration of electric vehicles into the power grid, and this remains an active area of research. Various algorithms were

Ref.	Battery swapping station	Charging station	Renewable energy integration	Microgrid	Distribution network	Electricity market	Optimization model
[62]	Y	N	N	N	N	Y	Mixed-integer linear programming
[90]	Y	N	Y	Y	N	Y	Mixed integer linear programming
[91]	Y	N	Y	Y	N	Y	Integer linear programming
[92]	Y	N	N	Y	N	Y	Mixed-integer nonlinear programming
[43]	Y	Y	N	N	Y	Y	Mixed-integer linear programming.

Table 4. Grid integration for BSCS.

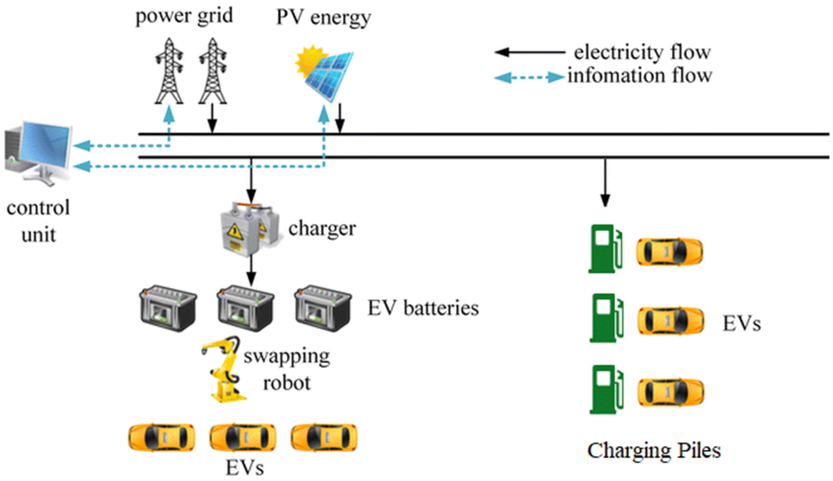

Figure 5. Grid integration of BSCS.

developed by studying the participation of EV aggregators in the energy market and support services market for smart charging [98]. Several uncertainties were addressed to demonstrate that smart charging policies can reduce network congestion and energy losses, as well as reduce power grid infrastructure investments for EV management [99, 100]. Grid integration, along with the BSS location, BSS scheduling, charging strategies, battery life, and renewable energy integration for the BSS, is discussed in a review article [101]. At the framework level, personal ownership of EVs will not be viable for two basic reasons. First, the market will have a large number of members, making it difficult to monitor the volume of individual exchanges. Second, their individual thresholds are lower than required to participate in control [102].

The Group operator/aggregator is required, with the ultimate goal of promoting collaboration between the power matrix and the EV group. The main function of the BSS aggregator is to trade energy demand while meeting the transportation needs of the EV fleet at minimal cost. Additionally, the aggregator increases its income by participating in auxiliary services. However, using it as storage equipment for grid purposes will shorten battery life [103]. Therefore, EV customers should be paid to support regulation by charging and discharging their EVs, which will reduce the aggregator's profit. The BSS can schedule batteries to operate in B2B, B2G, and G2B modes. To manage battery demand as well as the uncertainty of electricity prices, a robust model was developed by Sarkar et al. [62]. Aggregators can participate in the regulation market and the DA market using the BSS to maximize profit [90]. The integration of the BSS and the CS, considering renewable energy for the microgrid, distribution network, and electricity market, is given in Table 4.

The quality of service can be improved by reducing the average charging cost by avoiding inappropriate battery charging operations [91]. BSSs are connected to the microgrid (MG) with wind, PV, and geothermal units [92]. Used batteries can be repurposed in battery swapping and charging stations to enhance the economic profitability of the station. A Distributed Robust Optimization (DRO) approach is used to address uncertainty in BSCS operation and scheduling [43]. BSCSs can be integrated with renewable energy systems, considering the microgrid and electricity market as shown in Figure 5.

5.1. Transient stability of the grid with BSCS

The integration of V2G technology in BSCS enhances the transient stability of the power grid. Studies show that during disturbances, V2G-capable gridable vehicles (GVs) can support the grid by either drawing or supplying power, effectively damping load-angle and voltage fluctuations. When used alongside technologies like superconducting magnetic energy storage (SMES), V2G further strengthens grid dynamic performance [104]. In addition to supporting renewable integration and load management, V2G-enabled electric vehicles can enhance the transient stability of the grid. During large disturbances such as faults or sudden load changes, controlled power injection or absorption by PEVs can significantly reduce voltage and speed fluctuations and extend the critical clearing time by up to 40 %, thereby improving overall system robustness and resilience [105]. The integration of V2G technology has a significant impact on the transient stability of the grid. Studies conducted using a 33 kV/11 kV substation model in Amman revealed that V2G can enhance grid stability during disturbances, especially at higher EV penetration levels. Simulations showed improved frequency and voltage stability under various scenarios, demonstrating that controlled V2G operations can support the grid during peak load conditions and transient events [106]. It is essential to recognize V2G's role in enhancing grid reliability during disturbances to address the impact of V2G mode on the transient stability of the grid. By enabling bidirectional energy flow, V2G can help stabilize voltage and frequency fluctuations through rapid response mechanisms. Smart control strategies, predictive algorithms, and energy management systems integrated with charging and battery swapping stations further support grid stability during transient events, making V2G a valuable asset in future power networks [107]. The integration of V2G technology enhances the transient stability of the power grid by enabling Plug-in Hybrid Electric Vehicles (PHEVs) to supply power during sudden disturbances or peak demand periods. This capability is especially valuable when Renewable Energy Systems (RES) fall short or destabilize the grid due to their low inertia. PHEVs support grid stability by acting as distributed energy resources through peak load shaving and rapid response during transient events [108].

5.2. Integration of PV systems with BSCS

Low-voltage microgrids can be supported in dynamic environments by photovoltaic power plants (PVPPs) along with battery storage. The system guarantees voltage and frequency stability through efficient power management and integration with voltage source converters. With balancing load and reducing power quality concerns, these grid-connected renewable systems will improve the robustness and effectiveness of battery swapping and charging stations (BSCS) [109]. The integration of solar photovoltaic power into the grid presents challenges due to its fluctuating output, which can lead to overloading. To address this, a Constant Power Injection (CPI) control strategy has been proposed to regulate power flow into the grid by switching between MPPT and CPI modes. Such control approaches can support stable grid operation when integrating BSCSs powered by renewable energy sources [110].

Distributed Renewable Energy Generating Systems (DREGS) like solar PVs are added to microgrids, it can cause power quality problems like voltage drops and rises because they are not always on. The study suggests a system that uses an ultracapacitor and a Unified Power Quality Conditioner (UPQC) to improve grid performance and deal with these problems. Grid-supporting solutions like these are needed to make sure that Battery Swapping and Charging Stations work reliably in microgrids that use renewable energy [111]. Incorporating photovoltaic (PV) systems into the grid can support the energy needs of BSCS, especially as solar energy becomes a major power source. A novel active power control strategy with improved MPPT enhances the stability and efficiency of grid-tied PV systems, reducing voltage instabilities and power fluctuations. This approach ensures more reliable integration of renewable energy into BSCS, helping maintain grid balance under varying operating conditions [112].

Recent advancements in optimization techniques for renewable energy integration are highly relevant to BSCS coordination. For instance, the work by Rahul et. al. compares Particle Swarm Optimization and Cuckoo Search Algorithms for maximizing PV system efficiency under partial shading. These techniques dynamically adjust the PV system to ensure optimal performance, even when sunlight is unevenly distributed across the panels. Such methods enhance energy reliability, which is crucial for ensuring efficient and stable operation of energy-dependent BSCSs [113]. Quality of Service (QoS) can be provided by integration with the grid, reducing the average charging cost by considering the inappropriate battery charging operation in BSCS. BSCS can be connected to the wind, Microgrid, PV, and geothermal units to increase the profit. Providing electricity via batteries to the grid during the high demand for electricity on the grid will increase the profit of the BSCS. By developing proper strategies for interconnected BSS and CS, the profit of the station is considered during the peak load period, demand, and supply on a grid with renewable energy sources.

6. Energy management in BSCS

Electric vehicles are increasing in the market, and incentives are provided to promote the use of EVs as a replacement for conventional vehicles. Global EV sales are expected to increase in the Stated Policies Scenario (STEPS). Sales are projected to be nearly 45 million by 2030, up from about 14 million in 2023. This increase is also expected to approach almost 65 million by 2035. The sales share of EVs is also projected to rise, from about 15 % in 2023 to nearly 40 % in 2030 and over 50 % in 2035 [114]. EVs have

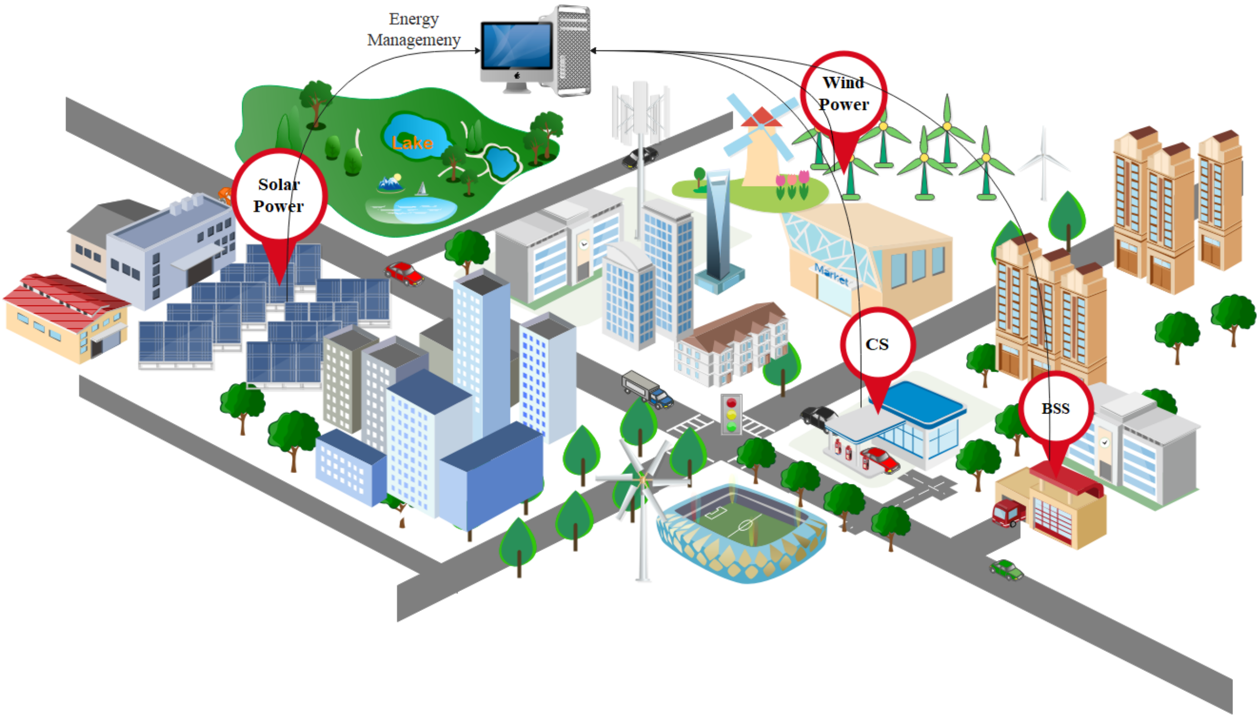

Figure 6. Energy management in BSCS.

many advantages, but one major barrier is the challenge of charging, which affects the mass adoption of EVs [115, 116]. In the BSS, a fully charged battery is obtained by exchanging an empty battery, and this exchange takes very little time. Ninety seconds are required to swap the battery of a Tesla Model S [117]. The battery price can be deducted from the EV price, and batteries can be rented to EV owners. With this, EV prices can be significantly reduced, as the battery constitutes a high share of the EV price [118].

Mobile BSS has also been developed in recent years to shorten EV charging. High-energy-density batteries must be used for the high range of EVs and the efficient use of batteries. In modern society, EV refueling systems contain various techniques such as BSS, fast charging, wireless charging, and slow charging, and serve as important juncture points between the power and transportation systems [119]. EV refueling systems usually deal with two critical challenges:

(1.) Large electricity consumers must reduce operational costs by managing energy consumption and maintaining system reliability [64];

(2.) Service providers need to maintain their business profile by providing quality of service for EV consumers [61, 120].

To recognize and balance the interaction between operational cost and QoS, analytical models are needed that capture the key characteristics of EV refueling systems. From this point of view, the important refueling systems BSCS are discussed [121]. The overall energy management system integrated with BSCS, along with the microgrid, is shown in Figure 6.

The trade-off between QoS requirements and electricity charging cost for a single BSCS is also maintained. As discussed above, fully charged batteries (FBs) are exchanged in the BSCS for depleted batteries (DBs) or empty batteries (EBs). The BSCS then charges DBs to FBs using appropriate charging strategies and considering the optimal charging time. The BSCS is among the best compared with other EV charging systems [61–64, 122]. A Cyber-Physical Energy Management System (CPEMS) is proposed to enhance economic operation and energy supply reliability [123]. From the EV perspective, the purchase price of EVs and range anxiety can be reduced. To enhance the operational flexibility and economic profitability of the BSCS, Retired Battery Energy Storage Systems (RBESSs) are developed, as shown in Figure 7 [43]. In this RBESS system, each EV battery-swapping demand is optimized to address the uncertainty of EVs. Moreover, the RBESS significantly improves the load characteristics of distribution networks.

The power system operators, whose requirements are more predictable, a BSCS aggregates uncertain EV charging demand into a specific charging component and can be restructured through suitable incentives. BSCS is considered a high-quality grid energy storage and a substantial energy buyer. Power system reliability can be maintained with less effort compared to battery charging operators, and the BSCS operator can gain additional flexibility. In a BSCS, the refueling system can be decoupled into battery swapping and battery charging procedures. These procedures give the BSCS full control and flexibility provided through available FBs for battery-charging operations.

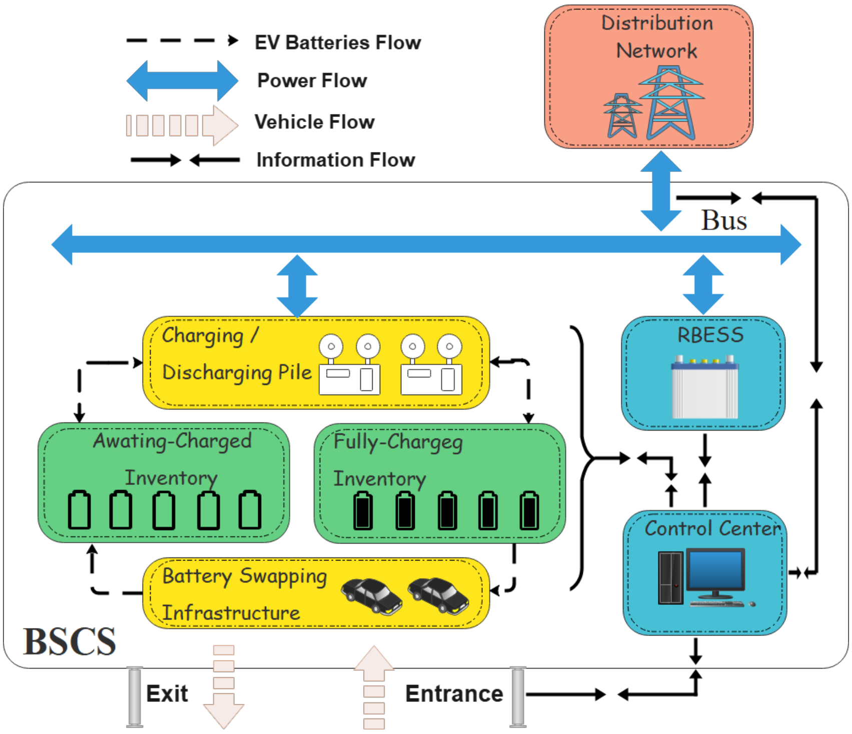

FIGURE 7. Power Flows in RBESS-BSCS.

Through payments from EV customers, along with participation in the electricity market, the BSCS can gain more profit. This is possible by providing ancillary services and by purchasing greener as well as cheaper energy.

7. BATTERY LIFE AT BSCS

The battery degradation cost is primarily based on the internal behavior of the battery, its life cycle, and the depth of discharge, along with consideration of BSS facilities [124]. Battery life can be reduced by overcharging or over-discharging, which causes an imbalance among the cells [125]. The load on the battery should be uniformly distributed among all cells, and all cells should be charged and discharged simultaneously using an optimal current. Charging or discharging at currents above or below the optimal level will affect the life of the battery [126]. The performance of the electric scooter prototype was monitored and equalized by considering the type of cell, manufacturing irregularities, storage capacity, and the charging and discharging cycles of the cell [127]. The average life of the batteries can be increased by planning a smart grid model along with scheduling operations for V2G charging and discharging [128, 129].

Online diagnostics of battery unit degradation are possible without any offline tests or supplementary sensors, by using the essential signals from battery module equalization. Additionally, the Worthiness of Replacement (WOR) metric is used for certain cells or units to map the health of the battery [128]. In this work, an online battery model degradation scheme is proposed using the signals of the battery module. The exact energy loss during a trip can be identified using WOR. Battery life is one of the most important aspects of EVs, and proper charging and discharging can increase battery life [127]. It is also important to plan a smart grid model to prevent premature battery depletion due to V2G operation. The average battery life can be increased by nearly 3.5 years by planning such a smart grid model. Such research is presented through optimal scheduling of charging and discharging of the battery with V2G technology [128–131].

Owners of EVs participating in V2G may be ready to trade their energy, but there are some constraints. It is not easy for all users to charge and discharge their batteries frequently without knowing battery status, especially since over 15 years of service, an EV has an average of 3 000 deep-discharge cycles. Therefore, research can examine different loading patterns on the grid to reduce battery depletion at charging stations by considering the available depletion cycles, real-time availability, battery capacity, and battery lifetime [132]. The Battery Management System (BMS) can be used to estimate the Remaining Useful Life (RUL) and the State of Health (SOH) of the battery [133]. These two parameters are critical for assessing the health of the Lithium-ion battery. An electricity price-based energy storage management system has been proposed to reduce the degradation cost of the energy storage system [134]. Thus, there is an opportunity to decrease battery degradation by considering energy management along with incoming vehicle data at the coordinated BSCS. The battery degradation cost of Autonomous Electrical Vehicles

(AEV) is minimized by a proposed distributed charging framework [135]. This framework can be implemented while considering the loading condition on the grid to decrease battery degradation. A hierarchical energy management strategy has also been proposed to handle the uncertainties of an integrated charging station and to minimize battery degradation [136].

The life of the battery depends on factors such as temperature variation during charging and discharging, the number of charge-discharge cycles, and the type of cell. As we know, increasing the battery life leads to profit maximization for both the BSCS and EV customers. Battery degradation can be minimized within the BSCS by considering the priority of EVs, the route of the EV, travel time, parking time, and electricity demand on the grid. Developing appropriate strategies can increase the efficiency of the battery by identifying effective charging times, electricity supply and demand, and periods of high peak load.

8. BSCS benefits

8.1. Customer perspective

From customer's point of view, the battery is the most expensive part of the EV. The BSCS scheme will allow customers to rent batteries instead of purchasing them with the EV, the latter estimated at nearly \$16–17k for 75 kWh in 2022 [140]. EV owners face issues such as upgrading the household electrical system for the charger, long charging times, and a limited number of CS and BSS. The time required to charge a 24 kWh battery with a Level 1 charger is about 15 hours using a household connection. This time can be minimized by upgrading from a Level 1 charger to a Level 2 charger, to about 7 hours with a capacity of 3.3 kW; however, this upgrade requires extra cost for the EV customer. Due to limitations of household current supply, upgrading to Level 2 is not possible [56]. Easy access to the BSS can minimize these problems. Some of the BSS benefits related to power systems are explained in [141].

8.2. Environmental benefits

The performance of EVs is directly related to the operation mode and charging method, as well as to energy savings and emission reduction. To enhance emission reduction and energy-saving effects for the customer as well as for the power system network, real-time battery swapping based on the price of electricity can reduce the impact on the power system network. The operation of battery swapping, the load on the power grid, and the electric taxi driver response impact the benefits of all the stakeholders. Carbon emissions are reduced by shifting battery charging to off-peak hours when cleaner energy sources are more available. The decentralized charging strategy also avoids peak load spikes, reducing the need for high-emission generators. This coordinated approach improves energy efficiency and has led to a 45 371.15 kg reduction in CO_2 emissions [142].

8.3. Cost-saving benefits

Cost-saving analyses of BSS and CS operations during off-peak hours have been conducted by various researchers. The studies show that aligning charging schedules with low-demand periods can significantly reduce operational costs. Off-peak charging helps avoid high peak-time tariffs and lowers strain on the grid. Results indicate a 29 % increase in grid usage due to night-time operations; yet this approach leads to 39 % lower operational costs compared with fast-charging stations during peak hours [143]. Using a dynamic time-of-use pricing strategy during off-peak hours can significantly lower BSCS operational costs. According to Qian Zhang, such a model balances user satisfaction and grid dispatch requirements, lowering electricity costs while improving load distribution. Their findings show that off-peak charging saves money for both users and grid operators, promoting cost-effective BSCS deployment [144]. To address cost-saving opportunities during off-peak hours, a lifecycle cost analysis of a grid-connected photovoltaic-wind hybrid system for battery swapping and charging stations reveals substantial benefits. By integrating an optimal control model that prioritizes energy use during low-tariff periods, the system achieved energy cost savings of up to 41.58 %. This strategy significantly reduces reliance on the utility grid during peak hours and supports economic operation with a payback period of 5 years and 6 months [145]. Integrating time-of-use (ToU) grid pricing with EV charging strategies, particularly during off-peak hours, has the potential to significantly reduce electricity costs for both EV owners and service providers by reducing peak demand-related charges and utilizing low-cost surplus energy [146].

9. Challenges and future trends

9.1. Feasibility

Battery-swapping technology is currently evolving with different topologies have been developed for swapping batteries. BSCS is a promising solution to charge or swap the battery. However, the battery-swapping design presents additional challenges for the technology. Battery replacement in BSS is a complicated task that requires robustness. Some companies in India, such as Hero Maxi, are offering battery-swapping technology. Additionally, EV batteries can also be charged at BSCS.

9.2. Infrastructure

Every charging station needs two batteries, one in the vehicle and the other in the charging station for the BSS. This can provide charged batteries to every EV customer with reliable service. In a comparison between BSS and charging stations, battery swapping technology is not the preferred option. Furthermore, to fulfill the requirements of different EV customers, BSCS provides both facilities charging and swapping

Country name	Quantity of BSS & BSCS	Quantity as of year	Company name	Ref.
China	3 000	April, 2025	Nio, Chinese EV company	[137]
Norway	15	July, 2024	Nio, Chinese EV company	[138]
Germany	17	June, 2024	Nio, Chinese EV company	[138]
India	630	June, 2024	Sun mobility, Indian EV Company	[139]

TABLE 5. Country-wise number of BSCS.

to EV customers, along with grid connectivity for profit maximization. The country-wise BSCS count is given in Table 5.

9.3. BATTERY OWNERSHIP

Batteries can be owned by EV owners or by charging station owners. EVs can be bought without batteries, which reduces the cost of EVs and benefits owners. EV customers can take charged batteries from BSCS and use them to drive the EV. Alternatively, EV owners can buy the EV with batteries and charge the EV at BSCS. BSCS owners can increase their profit by owning batteries and providing them to EV customers. Additionally, BSCS can make a profit by discharging batteries to the grid.

10. CONCLUSION

BSCS is evolving into a promising technological alternative to conventional battery charging at charging stations. It can reduce the burden on the electricity network and decrease the charging time for EVs. This research article presents a multidimensional assessment of BSCS deployment under different scenarios. In addition, BSCS can provide opportunities to increase profits for BSCS operators and aggregators and reduce problems related to range anxiety faced by EV customers. The research focuses on cost reduction, battery scheduling, and strategies for charging and discharging. The technique, location, infrastructure, and benefits of BSCS with respect to the power system operator, EV consumers, and the aggregator are addressed. Along with this, the significant challenges related to BSCS, for instance, battery ownership, battery degradation, feasibility, and interchangeability, are discussed in brief. A comprehensive review of energy management, BSCS charging, location, battery life, grid integration, various optimization techniques, and BSCS scheduling is provided.

This research examines planning, degradation, safety, and the challenges of positioning battery swapping as a standard refueling method for EVs. The BSCS approach offers expanded commercial opportunities for aggregators and other stakeholders. Coordinating BSCS with the power grid presents both opportunities and technical challenges. Effective integration requires strategic siting of facilities to ensure usability and reduce stress on localized grid segments. Implementing intelligent charging protocols is essential to balance charging demands with grid capacity, especially during peak hours, thereby supporting load leveling and enhancing overall stability. Coordinated BSCS represents a promising advance in technology over conventional EV charging infrastructure by significantly reducing vehicle downtime and increasing user convenience. The integrated model not only addresses limitations of traditional battery-swapping systems, such as battery compatibility and installation costs, but also introduces coordinated strategies for energy management. BSCS supports efficient power distribution and reduces strain on local networks by optimizing station placement and scheduling battery charging based on grid load conditions. Coordinated charging also helps mitigate the adverse effects of uncontrolled fast charging on battery longevity. BSCS not only supplies charged batteries but also functions as a flexible grid asset, enabling demand-side management during peak periods. Collectively, the BSCS framework contributes to a robust EV ecosystem that balances user needs, infrastructure efficiency, and long-term energy sustainability.

The extension of the present research work is possible by exploring the following research areas in the future:

- BSCS can provide a charging facility for different batteries and their variety of EVs as a fast refueling option.
- Need for optimization context for developing a business model for the BSCS corresponding aggregator, smart grid, and EV customer.
- Internet of Things (IoT) shall be added to BSCS as an ultimate technology offering services to smart chargers, intelligent transport, and AI-based facilities to the customers.
- Essential to focus on the statistics, learning predictions, and challenges that may arise through running and installation of the BSCS infrastructure.
- Feasibility check of BSCS businesses for the smart resident.
- Integration of renewable energy with BSCS to make it cost-effective for the aggregator, EV customers, and smart grids.

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