A Comprehensive Review on Electric Vehicle Battery Swapping Stations

Md Tahmid Hussain, Ahmad Bin Afzal, Altaf Hussain Thakurai, Ahmar Azim, Rashid Ahmed khan, Hasan Alrajhi, Mohd Rizwan Khalid, and Salman Hameed

Abstract This paper comprehensively reviews electric vehicle (EV) battery swapping stations (BSS), an emerging technology that enables EV drivers to exchange their depleted batteries with fully charged ones at designated stations. The paper aims to comprehensively understand BSS's technical, economic, and environmental aspects and its potential for widespread adoption. The review covers BSS design, operation, and maintenance, including the necessary infrastructure, battery management systems, and safety protocols. It also analyzes the economic viability of battery swapping compared to other charging technologies, taking into account factors such as capital and operational costs, revenue streams, and return on investment. Further discusses the environmental impact of battery swapping, including the potential reduction in carbon emissions, energy consumption, and resource depletion. Finally, the study examines the current state of BSS, including market trends, regulatory frameworks, and stakeholder engagement. The review concludes that BSS holds significant promise as a sustainable and convenient solution for EV charging. Still, several challenges remain to be addressed, including standardization, interoperability, and consumer acceptance. The findings of this study provide valuable insights for policymakers, industry stakeholders, and researchers working on the development and deployment of EV BSS.

Keywords Battery swapping techniques · Battery-to-grid · Fast charging · Range anxiety · Vehicle-to-grid

M. T. Hussain · A. B. Afzal · A. H. Thakurai · A. Azim · M. R. Khalid (✉) · S. Hameed
Department of Electrical Engineering, Aligarh Muslim University, Aligarh 202002, India
e-mail: mrk.rizwankhalid@gmail.com

R. A. khan
Department of Electronics and Electrical Engineering, University of Sheffield, Sheffield, England

H. Alrajhi
Department of Electrical Engineering, Umm Al-Qura University, Mecca, Saudi Arabia

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1 Introduction

The transition to electric vehicles (EVs) is critical to global efforts to reduce greenhouse gas emissions and mitigate climate change. While EV sales have grown recently, limited driving range and long charging times remain critical barriers to broader adoption. This is where battery swapping stations (BSS) come in, offering solutions to these challenges. The need for BSS in EV technology is driven by the growing demand for more efficient, convenient, and sustainable transportation solutions. BSS has the potential to offer a viable alternative to traditional charging methods while also addressing some of the challenges associated with EV adoption. BSS offers several advantages over conventional charging stations, including faster charging times, increased driving range, reduced infrastructure costs, reduced carbon footprint, new business models and revenue streams, and increased consumer convenience. As such, BSS is an area of significant interest and investment for policymakers, industry stakeholders, and researchers working on developing and deploying EV infrastructure. These points further explain the need for BSS in EV technology.

Range Anxiety

Drivers of EVs often worry about being stranded due to their restricted range on a single charge. As a result, drivers worry about the remaining charge in the battery which they are using. To avoid this problem, battery switching stations have been set up so that drivers may quickly and easily switch out their dead batteries for fresh ones and keep driving [1].

Infrastructure

Domestic migration propels the transition from rural to urban living in developing nations. Nearly everyone wants to live in a city, yet these areas weren't always adequately created and designed for the millions of new citizens. These cities were propelled by globalization into freshly established economic centers. Thus, finding fixed parking locations to charge EVs is consequently a challenge. The lack of charging stations for EVs can be partially remedied by setting up BSS. Locations for stations might be chosen to provide convenient access to charging infrastructure for drivers. This can be enormously beneficial in remote or rural places, where there may not be easy access to a charging station [2].

Time-Saving

Faster charging is possible with BSS than with standard outlets. Using conventional methods to charge an EV completely can take many hours, while battery swapping only takes minutes. This can alleviate some of the frustration drivers experience while waiting for their cars to charge [3].

Cost Effective

Charging stations for EVs can be expensive to install. Setting up a battery switching station may be costly, but over time, it may be cheaper than conventional charging methods. This is because, with regular battery swaps, batteries may be used more efficiently and for more extended periods [4].

Environmental Impact

While battery recycling cuts down on manufacturing, it can help the planet. This is due to the fact that battery switching can improve battery life, thereby reducing the overall need for new batteries. The adverse effects on the environment from making and disposing of batteries can be mitigated in this way [5].

The following is the remainder of the paper: Sect. 2 describes the different types of battery swapping techniques. Section 3 describes the functioning of BSS, and the problems associated with BSS have been described in Sect. 4. The impact of BSS on the distribution network and the usage of BSS as a battery to load (B2L) during peak loads are described in Sects. 5 and 6, respectively. Finally, Sect. 7 brings the conclusion of the paper.

2 Battery Swapping Techniques

To maintain electric transportation, the BSS replaces depleted batteries that have fallen below their predetermined state-of-charge (SoC) level with fully charged ones, and this process ensures the continuous operation of EVs. In the early nineteenth century, people proposed swapping batteries to solve the limited range of EVs like trucks and cars [6]. The concept involved using interchangeable batteries that could be replaced when necessary, and this replacement process was carried out using human labor. The initial implementation of a commercial battery exchange service that utilized the swapping strategy for EVs was called Better Place [7]. The utilization of the battery swapping method was restricted solely to electric cars and did not extend to heavy-duty vehicles like buses and trucks. As a result of requiring significant capital investment to create charging and swapping infrastructure and facing limited market penetration, Better place experienced substantial financial losses, leading to its eventual liquidation. In 2008, China commercially implemented the battery swapping method for electric buses during the Summer Olympics and switched the batteries of approximately 50 buses running on different routes [8]. Following the initial implementation during the 2008 Summer Olympics, the bus battery swapping method has been broadly adopted in various countries, including South Korea, Japan, China, and others. The different battery swapping methods are distinguished based on the location of the battery within the vehicle and the position at which the robotic arm is applied. Figure 1 shows different battery swapping techniques, these are listed below:

A ***Sideways Battery Swapping***

When changing the batteries in an EV, the exhausted battery pack is horizontally pushed out from underneath the car and is replaced with a fully charged one. This

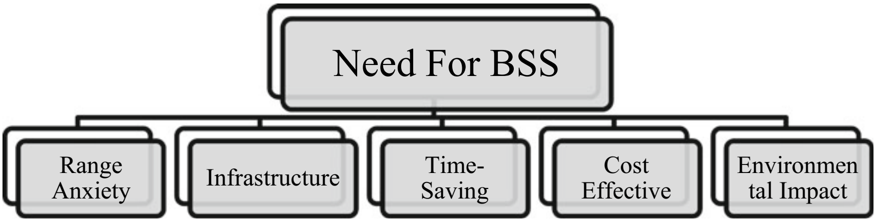

Fig. 1 The need for BSS technology

technique is known as sideways battery swapping. Additionally, since the battery can be swapped from the side, it does not require the space and infrastructure needed for a vertical battery swapping station, which can be more expensive to install. It is commonly utilized for vans and other vehicles best suited for a sideways position during battery swapping.

B ***Bottom Battery swapping***

This is used in cars with bottom-mounted batteries. The automobile is placed on a raised platform by the swapping station, and the batteries are changed from the bottom using an automation arm and other peripherals that are often located below ground. The station is constructed to raise the car on an elevated platform. At the same time, the battery exchange occurs from below using a robotic arm and various devices, typically positioned beneath the ground level.

C ***Rear Seat Battery Swapping***

In order to use this method, the vehicle's rear seats must be removed, and the spot where the seats once were must be filled with a battery pack. Tesla had suggested using this approach, but the business eventually decided against it. This battery swapping technique applies to vehicles with batteries placed toward the back, commonly seen in cars with spacious trunks.

D ***Vertical Battery Swapping***

This is the most common battery swapping technique. It involves lifting the entire battery pack out of the vehicle and replacing it with a fully charged one. This method requires specialized equipment and a dedicated swapping station with hydraulic lifts to remove and replace the heavy battery pack. Vertical battery change does provide some difficulties, though. Installing the charging stations needs significant infrastructure investment, and standardizing battery sizes and interfaces across various EV models is also necessary. Furthermore, it can take a while to finish, which could be longer than the time required to recharge a battery using a rapid charging station.

3 Functioning of Battery Swapping Stations

Implementing the technique of swapping vehicles, vans, and buses requires extensive planning, as shown in the block diagram in Fig. 2. The accessibility of batteries and chargers, cloud-based data storage and management, and interaction among components to ensure interoperability should all be considered during this planning. The BSS relies on constant communication between the smart vehicle, exchange station, and information system to function properly. The information system will facilitate the vehicle's communication with the station [9].

WAVE communication will allow communication between the vehicle and the information system. In contrast, the station will communicate via the local Internet. The vehicle will notify the information system and request a battery switching service when the battery dies. The information system will then inform the station of the vehicle's location, anticipated arrival time, and identifying information. This will allow the station to prepare the battery in advance to be ready when the vehicle arrives (Fig. 3).

When the car approaches the station, the driver swipes their registration card, and the computer verifies the information. This information pertains to vehicles and their batteries, as well as past swaps and purchases. All data should be stored in the cloud and made available to the owner of the station and client for full operational transparency. After swapping, the old battery is inspected for signs of charge, degradation, age, and total number of charge/discharge cycles [9, 10]. The charging station's key components are as follows:

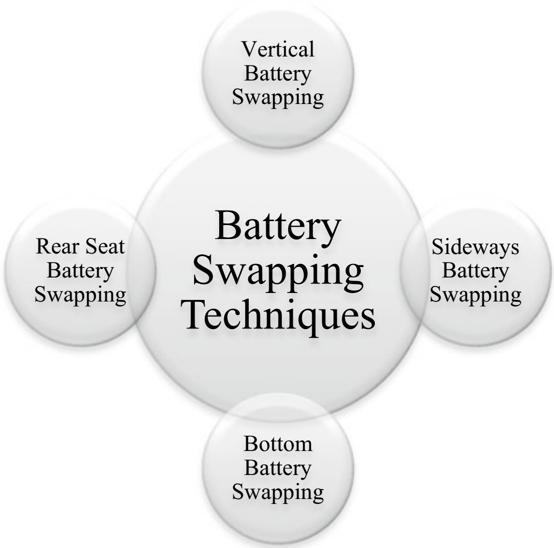

Fig. 2 Battery swapping techniques

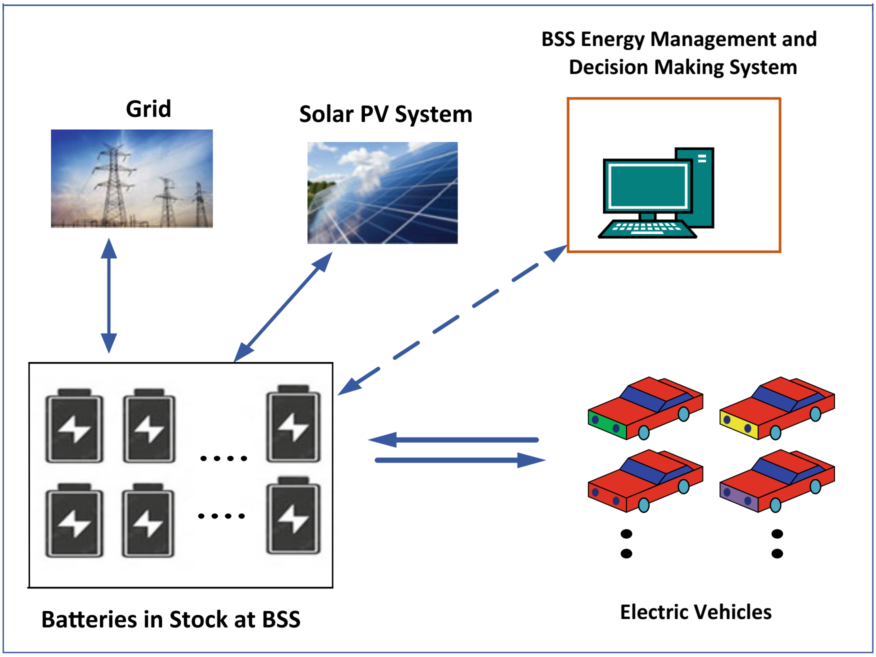

Fig. 3 Working of battery swapping station

- Control room (for managing and observing the BSS's overall operation).
- Battery racks and charging racks together.
- Track swapping (the area where the batteries are when the track is switched).
- The route where the automobile is when being switched out.
- changing the service room for the robot, battery, and charger.
- Service area for additional BSS parts.

As is customary at petrol stations, the first driver to the BSS should be given priority over those who arrive later. The batteries must be recharged right away after the exchange in order to serve the demands of all customers visiting the BSS. The range and the need to switch batteries while using a BSS that is built in should both be maximized [11].

A more adaptable and effective EV battery swap design is needed due to constraints, including location, the availability of BSSs, and station congestion. Passive mode and active mode are both examples of battery swapping. The goal of having enough power to drive an EV whenever and wherever is not met while the vehicle is dormant. To change the battery pack, drivers must travel to the BSS. There may still be a long wait for a battery at that time due to the station's remote location and low battery stock [10].

In the active mode, a second vehicle drives up to one whose battery is low or dying so that they can switch batteries. Recently, a unique system for rapidly replacing EV batteries was developed [12]. Be put in a mobile BSS, which is a modified vehicle. Battery replacement and removal are performed simultaneously. As a result, the exchange procedure moves quickly and only needs a short amount of time (approximately three minutes in the testing setting). The swap can take place whenever it happens to be comfortable for all involved by using a vehicle such as the BSS [13].

4 Problems Associated with BSS

The restricted driving range, high purchase price, scarce supply of charging stations, and lengthy charging times are some barriers to EV adoption. There are further psychological problems, such as driver range anxiety and resistance to new technologies. The majority of the hurdles are effectively shortened by battery swapping technology. But the situation is more complicated than this, and below are the difficulties with battery swapping technology (Fig. 4):

A *Standardization*

The market is dominated by technology because of its brand compatibility and cross-platform capabilities. A battery swapping system can remain the norm only if battery packs from different manufacturers are interchangeable. This straightforward approach needs approval from the manufacturer. Considering all possible technological possibilities, EV driving scenarios, potential failure causes, and BSS viability, standards should be formulated to verify the minimal time needed to change batteries throughout their service lives.

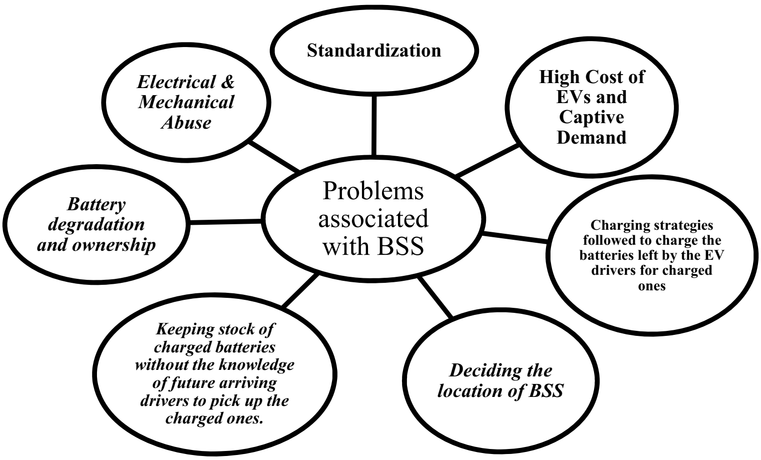

Fig. 4 Various problems associated with BSS

B *High Cost of EVs and Captive Demand*

Even though the total cost of ownership of an electric-to-wheeler is approaching that of an ICE equivalent, the EV scale-up is prevented by the EV's acquisition price, which is still 30–50% higher. In this cutthroat marketplace for 2-wheelers, batteries can be expensive to repair. Investments in real estate, equipment, batteries, and inventory are needed to move batteries. Exchange stations must be placed in busy places where customers can quickly access them, which drives the rent. Asset utilization is required for capital-intensive businesses.

C *Charging strategies followed to charge the batteries left by the EV drivers for charged ones*

In BSS, multiple charging schemes have been proposed and investigated; each one aims to maximize the efficiency of the charging process. The concept of battery-to-grid (B2G) and vehicle-to-grid (V2G) technology is the foundation for one approach to this problem.

EVs can act as mobile energy storage units in B2G and V2G systems, feeding electricity back into the grid during high demand. This idea can include BSS, where EV drivers can leave their batteries charged during off-peak hours and drained during peak hours to help balance the grid's energy supply and demand.

Battery exchange stations commonly use two charging methods:

1. *Fast Charging*

With high-power chargers, fast charging can fully replenish depleted batteries in a fraction of the time it would take using conventional methods. When there is a large demand for battery replacements and a short turnaround time is necessary, this method is often employed. While fast charging can replenish a depleted battery in as little as 5–10 min, it can shorten its useful life due to the high heat generated during the process [14, 15].

2. *Slow Charging*

The batteries are charged slowly over a long time using low-power chargers. This strategy is often implemented when the need for battery replacement is low and a longer turnaround time is tolerable. Although slow charging can take several hours or even a whole night, batteries are safer and do not affect their useful life [14, 15].

Depending on the needs of its clientele, some BSSs may also use a hybrid approach, including both rapid and gradual charging. Battery types (such as lithium-ion or nickel-metal hydride) and their respective manufacturers' guidelines can dictate how best to charge them. It's important to remember that BSS must meticulously manage its charging procedures to guarantee that batteries get fully charged and returned to service. Both overcharging and undercharging can shorten the battery's useful life, reduce its performance, and even pose a safety risk.

D *Deciding the location of BSS*

A BSS's accessibility and convenience to drivers of EVs are greatly influenced by its placement. Location is crucial to a BSS's business success. By carefully spacing BSS, range anxiety, a significant drawback of EVs, can be mitigated [16].

BSS location also affects system running expenses. Using an aggregator or selecting a location based on wind power are different business models. These models determine the appropriate position for all network BSSs. BSS location is crucial for optimizing charging and discharging operations to balance grid supply and demand [17, 18]. Putting the BSS in the right spot can ease concerns about the EV's range. That could encourage more people to drive EVs. A trade-off between EV path, grid energy losses, and BSS location arises from optimal EV planning considering swapping station positions [19]. The location of a swap station can be determined cheaply and effectively with a GPS position-based framework. The ideal location for the BSS can only be determined by compiling data from the traffic network and electricity requests. A site can be determined by looking at the spatial distribution of the demand for swapping and the mean distance error (MDE) between the locations [20].

Day-ahead energy and reserve capacity markets are recommended for optimal BSS operation. Location determines BSS price, which schedules battery charging and discharging. The BSS then submits synchronized day-ahead energy and reserve capacity bids. Aftermarket clearing, the BSS may mimic the process to calculate the locational marginal prices (LMP) and reserve capacity prices. Hence, the BSS can improve grid stability and profitability while operating more effectively [21]. As the power system moves toward a smart grid, BSS will help maintain grid stability and dependability. A smart grid's optimum BSS locations have been suggested. BSS can be deployed where they will have the most significant impact with the fewest costs, improving the smart grid's dependability and efficacy [22].

Vehicle and electrical network constraints are the two primary categories of limitations impacting the ideal BSS location. Vehicle network restrictions include travel distance, budget, BSS, traffic flow, and EV driving range. Power flow, charging demand, voltage, and thermal limits are electrical network limits. These restrictions are critical for BSS and microgrid efficiency, as they determine the best BSS placement.

E *Keeping stock of charged batteries without the knowledge of future arriving drivers to pick up the charged ones*

Concerns may arise from keeping a supply of charged batteries on hand without knowing when drivers will arrive to pick them up. The most fundamental problem is that batteries can lose their charge over time, especially if they aren't used or replaced frequently. Since the batteries may need to be recharged or replaced more often, this might be a waste of time and money. The research advises working with drivers to build a system for scheduling battery pickups and ensuring the batteries are adequately used. Using battery management software to track power consumption and anticipate when batteries will require charging is one option, as is establishing lines of communication with drivers to schedule pickups. A study highlights the importance of excellent battery management systems and scheduling tools to reduce the batteries needed to fulfill demand in EV fleets. Findings from the study suggest that by taking a proactive and coordinated approach to battery management, EV fleets can improve their sustainability and cost-effectiveness by using their battery resources and reducing waste. Therefore, these studies stress the need for proper battery management systems and scheduling tools to be implemented in EV fleets to maximize battery utilization. Coordinating with drivers and using predictive analytics to manage battery inventories may reduce waste, improve sustainability, and cut costs for EV fleets [23, 24].

F ***Battery degradation and ownership***

Performance degradation reduces battery charge range. Therefore, customers would prefer the new battery packs over older ones because they will provide poor energy storage due to deterioration, affecting EV mileage. New battery packs with much reduced operational cycles will satisfy customers. A car owner will never have any ownership rights to a battery pack. This has several benefits. Because the owner doesn't own EVs, the overall cost is reduced. Instead, he will pay a lease fee and never get the battery back. Each transaction or monthly can be charged for this. The latter leasing method is expensive because it requires two battery packs and the changing station service price.

G ***Electrical and Mechanical Abuse***

BSS must clean batteries to avoid high-resistance connections from shorting. Electrical connectors and cables must last thousands of swaps. The BSS's main electrical components include a distribution transformer, AC/DC chargers, battery packs, and a battery energy control module. BSS requires high power (33–11 kV) and varying charging levels for electrical safety.

The BSS mechanical framework comprises vehicle platforms, battery lifts, vehicle alignment equipment rollers, battery conveyor shuttles, and battery storage rails and racks. Swapping EV battery packs should not cause mechanical damage. It should survive repeated EV-BSS switching.

5 Impact of BSS on Distribution Network

For extensive EV-grid integration, the power interaction between the distribution grid and EVs has emerged as a critical issue [25]. The BSS views the battery as a charging element instead of the conventional EV charging station. Its arrival suggests a new way for EVs and the grid to interact regarding energy. The efficiency of the EV-grid power interaction is increased by the BSS operating mode, which enables an EV to quickly swap out an empty battery for a full one while leaving the depleted battery in the BSS for charging. In contrast, BSS may make reasonable plans for battery charging and discharge depending on power costs and the condition of the distribution system, which enhances the efficiency and dependability of distribution network operations [26, 27]. Studying the impact of BSS connections on the distribution network is therefore crucial.

BSS positively and negatively may significantly impact the distribution network. Here are a few possible effects

A *Increased demand*

BSS can increase the demand for electricity in a particular area, especially during peak hours when many drivers may need to swap their batteries. This increased demand could strain the distribution network and require upgrades to the local grid infrastructure to ensure it can handle the load. This can overload distribution transformers leading to more power outages, equipment damage, and increased maintenance costs [28].

B *Cost implications*

Depending on the location and scale of the BSS, significant costs may be associated with upgrading the distribution network to support it. Additionally, ongoing maintenance and operational costs may need to be considered [29].

C *Increased reliability*

BSS could help improve the reliability of the distribution network by being utilized as an alternate power source to inject electrical energy into the grid to lessen load shredding when the grid fails [30].

D *Potential for renewable integration*

BSS could provide a valuable tool for integrating renewable energy sources into the grid, which could help reduce its potential negative impacts on the distribution network. Some ways in which renewable energy can be integrated with BSS to minimize their effects are by installing solar panels at or near the BSS, which can provide a reliable source of renewable energy that can be used to charge the batteries, and by using wind turbines in areas with good wind resources. For example, batteries charged by solar panels during the day could be swapped out and used to power EVs at night when demand is high [10, 31].

The adverse effects of BSS on the distribution grid can be mitigated by integrating renewable energy sources, as mentioned above, by using optimal charge scheduling and giving different priorities to vehicles while charging.

The practice of planning the charging of EVs to maximize efficiency and reduce the cost of charging is known as optimal charge scheduling. This entails figuring out when and how long each car should be charged, considering things like the availability of renewable energy sources, the price of electricity, and the grid's condition [32]. In [33] proposes an optimal charging schedule for EVs in solar-powered charging stations based on day-ahead predictions of solar power generation. Optimal charging scheduling can also effectively reduce the potential negative impacts of BSS on the distribution network. By implementing time-of-use pricing, smart charging systems, battery management, V2G technology, and demand response programs, we can help reduce the peak demand on the distribution network and ensure a more reliable and sustainable energy system [34, 35].

Another tactic to lessen the possible harm caused by BSS on the distribution network is prioritizing the charging of batteries. This can be implemented by using the following steps [36–39].

E ***Charging light vehicle batteries first***

During peak hours, the demand on the distribution network can be decreased by charging the batteries of light vehicles first. The overall stress on the distribution network can be minimized by prioritizing these vehicles first, which consume less electricity than heavy-duty vehicles.

F ***Charging batteries based on battery state-of-charge***

Low state-of-charge (SOC) batteries can receive priority during charging. This can ensure that the weakest-powered cars have the fuel they require to continue their journey. By reducing the time vehicles spend at the exchange station, the demand on the distribution network may be lessened.

G ***Charging batteries based on the type of EV***

Different types of EVs require different amounts of energy to charge. The overall demand on the distribution network can be reduced by prioritizing charging EVs with lower energy requirements. For example, a smaller EV may require less energy to charge than a more extensive, heavy-duty EV.

H ***Charging batteries based on the time of day***

Charging batteries during off-peak hours can help reduce the peak demand on the distribution network. By prioritizing charging during times when renewable energy sources are most abundant, the use of non-renewable energy sources can be reduced, minimizing the carbon footprint of charging EVs (Fig. 5).

6 Usage of BSS as a Battery to Load (B2L) During Peak Loads

Battery to load refers to the use of batteries to supply power directly to the load during peak hours, which helps reduce the stress on the power grid. The BSS can store excess energy during off-peak hours and supply it to the load during peak hours. This can help reduce the load on the power grid and prevent brownouts or blackouts. The usage of BSS as B2L during peak loads can offer several benefits to the grid. These benefits can be explained below as follows:

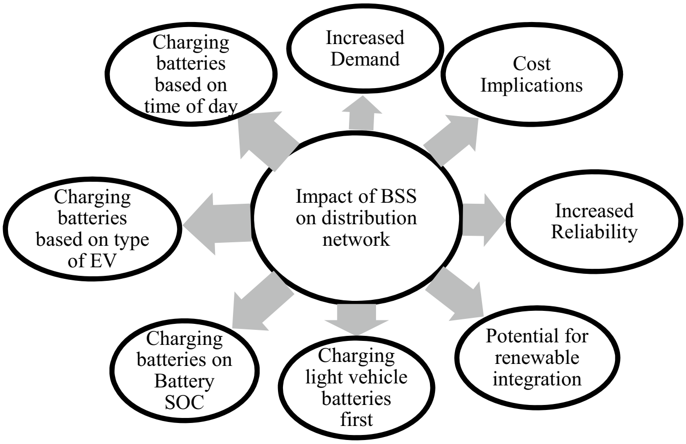

Fig. 5 Impact of BSS on distribution network

A ***Load management***

By using BSS as a source of energy during peak loads, the load on the grid can be managed more effectively. This can help prevent overloading and improve the stability and reliability of the grid.

B ***Cost savings***

Using BSS as an energy source during peak loads can help reduce the need for expensive infrastructure upgrades or the use of expensive peaking power plants. This can result in utility cost savings and potentially lower consumer electricity rates.

C ***Environmental benefits***

If the BSS is powered by renewable energy sources, using them as a source of energy during peak loads can help reduce greenhouse gas emissions and promote a more sustainable energy system.

D ***Improved grid resiliency***

Using BSS as a source of energy during peak loads can improve the grid's resiliency by providing backup power in the event of a grid outage or other emergencies.

However, there are also some challenges to using BSS as a source of energy during peak loads. These include the need to ensure that the batteries are charged and available when needed, the potential for equipment damage or failure, and the need to manage the energy distribution from the BSS effectively. Overall, the usage of BSS as a battery to load during peak loads can offer several benefits to the grid. Still, it requires careful planning and management to ensure its effectiveness and reliability (Fig. 6).

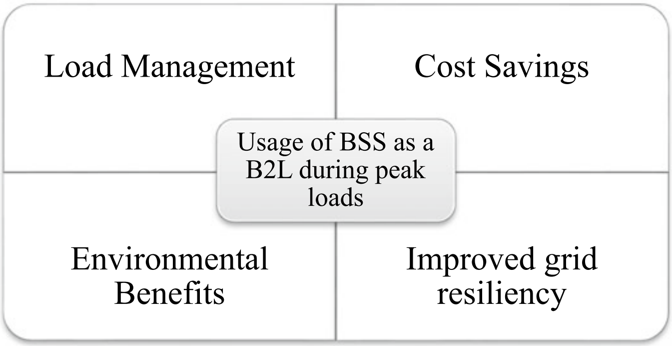

Fig. 6 Usage of BSS as battery to load

7 Conclusion

This paper discusses the concept of battery swapping stations (BSS) for electric vehicles (EVs). This concept is superior to the EV charging station when compared in many aspects, like the time the EV driver needs to spend at the EV charging station. In addition, various problems associated with the BSS are discussed, like standardization of EV batteries, the high cost and capital required for installation, and deciding the optimal location of BSS along with the capacity. Moreover, the impact of BSS on the distribution network is discussed; also, the usage of BSS in the battery to load (B2L) mode is discussed to meet the high load demands during peak hours.

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