A Comprehensive Review on Electric Vehicles Smart Charging: Solutions, Strategies, Technologies, and Challenges

Omid Sadeghian[1], Arman Oshnoei[2], Behnam Mohammadi-ivatloo[1,3*], Vahid Vahidinasab[4], Amjad Anvari-Moghaddam[2]

[1]Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz 5166616471, Iran

[2]Department of Energy (AAU Energy), Aalborg University, 9220 Aalborg, Denmark

[3]Department of Electrical Engineering, Mugla Sitki Kocman University, Mugla, Turkey

[4] Department of Engineering, School of Science and Technology, Nottingham Trent University, Nottingham NG11 8NS, UK

[*]Corresponding author (mohammadi@ieee.org)

Abstract: The role of electric vehicles (EVs) in energy systems will be crucial over the upcoming years due to their environmental-friendly nature and ability to mitigate/absorb excess power from renewable energy sources. Currently, a significant focus is given to EV smart charging (EVSC) solutions by researchers and industries around the globe to suitably meet the EVs' charging demand while overcoming their negative impacts on the power grid. Therefore, effective EVSC strategies and technologies are required to address such challenges. This review paper outlines the benefits and challenges of the EVSC procedure from different points of view. The role of EV aggregator in EVSC, charging methods and objectives, and required infrastructure for implementing EVSC are discussed. The study also deals with ancillary services provided by EVSC and EVs' load forecasting approaches. Moreover, the EVSC integrated energy systems, including homes, buildings, integrated energy systems, etc., are reviewed, followed by the smart green charging solutions to enhance the environmental benefit of EVs. The literature review shows the efficiency of EVSC in reducing charging costs by 30%, grid operational costs by 10%, and renewable curtailment by 40%. The study gives key findings and recommendations which can be helpful for researchers and policymakers.

Keywords: Electric vehicles smart charging; electric vehicles aggregator; vehicle-to-grid; charging infrastructure; smart charging challenges.

1. Introduction

The conventional transportation sector is responsible for nearly 25% CO2 emissions [1] and 55% global oil consumption [2]. Nowadays, the development of electric vehicles (EVs) is ongoing as a critical action for the direct reduction of CO2 emissions. The main drivers for developing EVs are the energy crisis [3] and environmental issues [4], including global warming and local air pollution, particularly in cities [5]. The research outlines the role of EVs in electrifying active buildings as one of the decarbonization approaches [6]. EVs can act as prosumers in electric systems by participation in demand-side response programs [7]. The implications of EVs include economic, environmental, and technical impacts [8]. The economic implication is related to the power exchange between EVs and the power grid through vehicle-to-grid (V2G) technology. V2G benefits both EV owners and the power system by decreasing the share of high-cost generators, such as gas turbines in peak-load hours, in exchange for payment to EV owners [9]. Environmental impact is related to emissions over an EV's life, i.e., the summation of the electricity generated to power EVs and the direct tailpipe emissions of EVs. According to this, EV charging from a coal-fired power grid causes a higher overall emission for EVs than EV charging from other sources of energy such as gas natural gas [8]. To overcome this challenge, green (i.e., renewable) energy deployment for charging EVs is ongoing [10]. Moreover, the technical aspects are related to EVs' negative and positive impacts on the power system due to the difference in temporal and spatial characteristics of EVs' charging [11].

The battery charging of EVs is mainly accomplished nightly since daily travel with vehicles significantly limits the charging time to night hours. With the proliferation of such vehicles, early night charging of cars negatively impacts the power grid characteristics such as overloading and fast ramping of power generators. In addition, the increased penetration of EVs may deteriorate grid characteristics, such as feeder congestion, undesirable peak demand, increased power loss, reduced load factor, harmonic distortion, phase unbalance, etc. [12]. These negative impacts are because of the synchronicity of EV charging with the peak load [13]. Electric vehicles smart charging (EVSC) [14] is the solution to overcome the mentioned challenges. EVSC can effectively manage EVs' charging process, particularly during the night, to meet the network technical constraints. Based on statistics, on average, the vehicles travel for only 4–5% of the time, and the rest of the day, they are parked in home garages or parking lots [15]. The aggregated batteries of such vehicles could be seen as large-scale, but distributed energy storage systems [16] and are beneficial for improving the network characteristics through EVSC.

The coordinated charging of EVs under an EVSC mechanism leads to the EV owners' satisfaction and consideration of grid characteristics for selecting the number of EVs and related charging/discharging locations in each time interval [17]. In addition to considering EV owners and power network technical constraints, the EVSC procedure should also consider the maximum usage of renewable energy generation (subjected to technical limitations) in renewable-based power networks [5]. From the power grid's perspective, EV charging through EVSC could help maintain/improve the power grid operating condition while providing additional services to the operators, such as frequency regulation [18]. The schematic diagram of EVSC is shown in Fig. 1. EVSC can recharge EVs in decentralized or centralized states. The connection of EVs to smart homes is a type of decentralized charging, whereas, in centralized charging, batch charging of EVs located in a parking lot (at a building or public parking) is conducted. In addition to timely charging of EVs and providing ancillary services, EVSC can also decrease the energy cost for EVs' charging by up to 60% [19].

As mentioned, in addition to neutralizing the negative impacts of nightly charge, EVSC contributes to improving the power grid characteristics through ancillary services [20]. Different ancillary services such as power quality services, grid loss reduction, voltage (or reactive power) support, frequency response services, constraint management, etc., may be provided by EVSC [21]. For proving ancillary services by EVs (through EVSC), both vehicle-to-grid (V2G) and grid-to-vehicle (G2V) strategies are needed to enable bidirectional power exchanges [22]. In the V2G mode, EVs charge to improve the grid characteristics in peak load hours, whereas in the G2V mode, EVs are charged to meet the batteries' energy needs [23]. In addition to managing the peak load, EVSC can also improve the load factor by charging parked EVs during low-demand hours and exercising load valley filling actions [24]. The EVSC can also be conducted to meet other techno-economic objectives such as lowering charging costs, improving voltage profile, mitigating peak load, and reducing power losses [25]. For the objective (or objectives) considered in the EVSC strategy, the constraints related to EVs and the power grid must be regarded as [26].

The EVSC procedure is accomplished under an EV aggregator as a person or an authority [27], which is vital in coordinating EVs for smart charging [28]. The EVSC can overcome the complexities of EV charging caused by differences in travel patterns, state-of-charge (SoC) levels, energy needs, and the tendency of EV owners for nightly charging of cars simultaneous with the peak load hours [29]. The EV

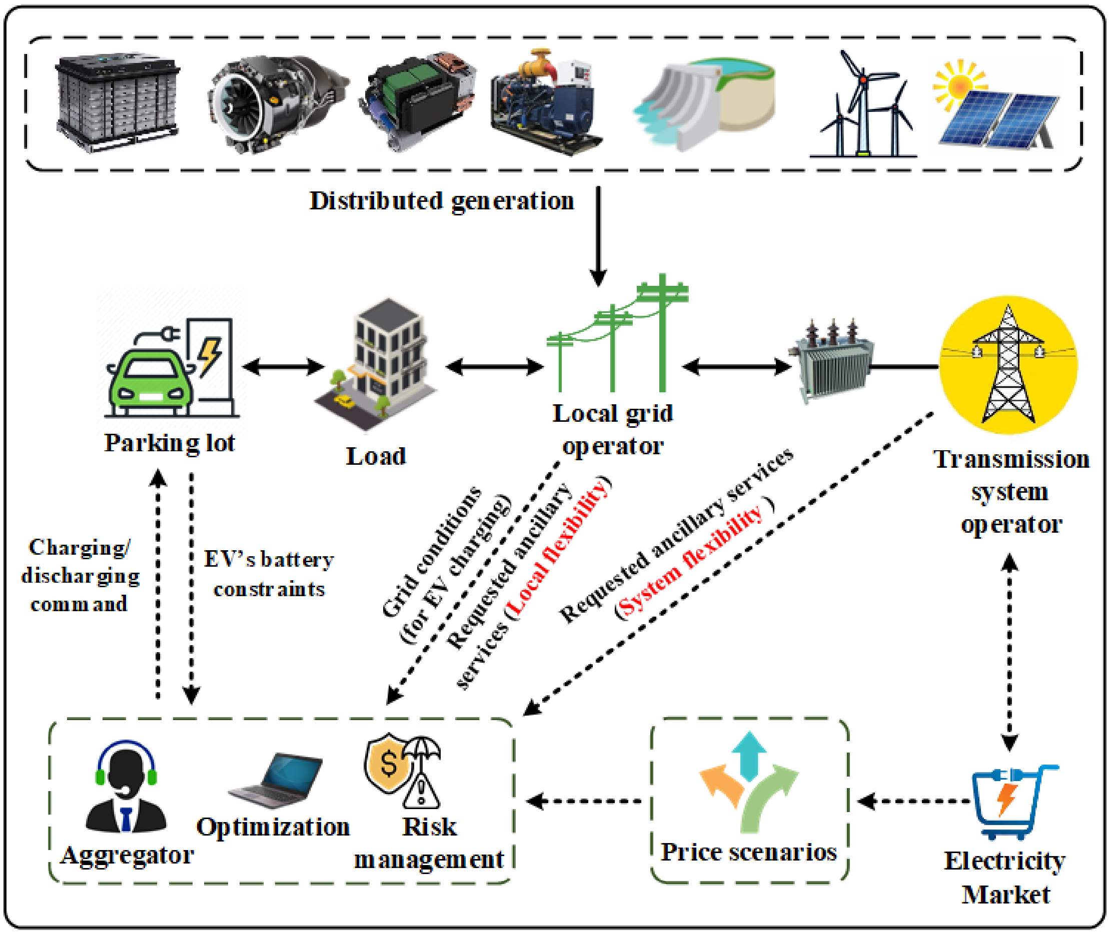

Fig. 1. Schematic diagram for electric vehicles smart charging in power systems.

aggregators move the charging time of EVs to the low-demand hours of the night as far as possible, considering the time it takes for the batteries to store the energy needed for the next day's travels.

EVs can recharge through homes, buildings, public parking, charging stations (regular AC charging stations or DC fast-charging stations), battery swapping/switching stations [30], and even energy exchange with other EVs [31]. The charging points can be energized through a utility grid or local energy systems that accommodate various energy sources [32]. From the viewpoint of system type, EVs can charge through distribution systems, microgrids, energy hubs, virtual power plants (VPPs), etc. [33]. For instance, wind and solar power stations can connect to the main grid or directly connect to a local grid like a microgrid to charge the EVs' batteries. Stationary energy storage systems can also charge EVs and mitigate renewable power generation intermittencies.

There are different challenges regarding the implementation of EVSC. The main challenge, in this regard, is providing and managing the energy required for EV charging [34]. Information and communication technology (ICT) used in EVSC systems for efficient operation management and coordination, together with the fast and reliable communication infrastructures needed to bridge the charging systems and the EVs, is another subject matter which needs attention. For EVSC, forecasting the EVs' load is also vital to keep their optimal operation while meeting the grid's requirements. Although predicting the load of each EV is not possible due to the difference in EV travel patterns [35], the total load of EV fleets can be predicted by existing methods, such as machine learning methods, support vector machines, and time-series models [36]. The electricity market consideration for EVSC is another point have to be considered since such market environments are competitive. This competition among market players leads to price uncertainty [37] and complication in EVSC. Technical considerations related to the EVs' SoC level required for the next day when maintaining the grid characteristics (such as the system stability and power quality) are another barrier to the implementation of EVSC [38]. In addition to the tasks mentioned above, an EVSC procedure should also cover the growing penetration of EVs in the system [39] since the EVs load will become a considerable part of the utility load soon [40].

In the literature, several review works have been accomplished related to EVSC. In [41], the authors have discussed the barriers and opportunities that can directly or indirectly affect the economics and development of public charging infrastructures. The positive and negative influences of charging EVs on power systems have been reviewed in [42]. In another survey [2], charging solutions and optimization techniques have been studied comprehensively. In [25], EV charging has been reviewed from the viewpoints of charging solutions, optimization objectives, and optimization techniques. In another review work [36], the authors have focused on charging scheduling (centralized and decentralized), data mining (unsupervised and supervised), and load forecasting (short-term, mid-term, and long-term) aspects of EV charging. Furthermore, in [43], control methods, optimization objectives, centralized/decentralized charging, and negative impacts of EV charging on the power system have been reviewed. Reference [44] has discussed EV charging in Germany by focusing on charging techniques, standards, and the development of EV technologies. Moreover, some other surveys have focused on available chargers [45], wireless charging technologies [46], cybersecurity of on-board charging systems [47], dynamic pricing mechanism for EV charging [48], the participation of EVs in frequency regulation of power systems and related influences [49], power quality improvement effect of EVs [18], energy exchange among EVs [31], and application of green energy to supply the EVs' load [10].

Based on the literature reviewed above, there is no comprehensive review study related to EVSC. Each review work mentioned above has focused on one or a limited number of EVSC aspects. Accordingly, this paper covers this gap by comprehensively reviewing various aspects of EVSC, including the smart charging solutions, strategies, technologies, and challenges for EVs. In this regard, the role of the EV aggregator, charging methods, and potential objectives of EVSC are discussed. Furthermore, the ancillary services, load forecasting of EVs, and EV penetrated energy systems are outlined. The related enabling technologies (infrastructure), including the charger (wired and wireless chargers) and ICT infrastructure, are also reviewed. Moreover, a detailed discussion on the existing challenges for implementing EVSC, including the grid-related challenges, electricity pricing for EV charging, security challenges, etc., are presented. Finally, "green charging" as an environmentally-friendly option to supply the energy demand of EVs will be discussed in this paper. The main keywords of the previous works related to EVSC are illustrated in a VOSviewer graph [50] in Fig. 2. The main objectives of this work are also highlighted as follows:

a) To present a comprehensive review on EVSC together with their benefits and challenges,

b) To review the charging methods for EVs and related characteristics and impediments,

c) To enumerate the ancillary services that a smart charging mechanism can provide

d) To discuss the challenges of integrating EVs into energy systems.

e) Charging costs and grid operational costs can be reduced by 30% and 10% via EVSC

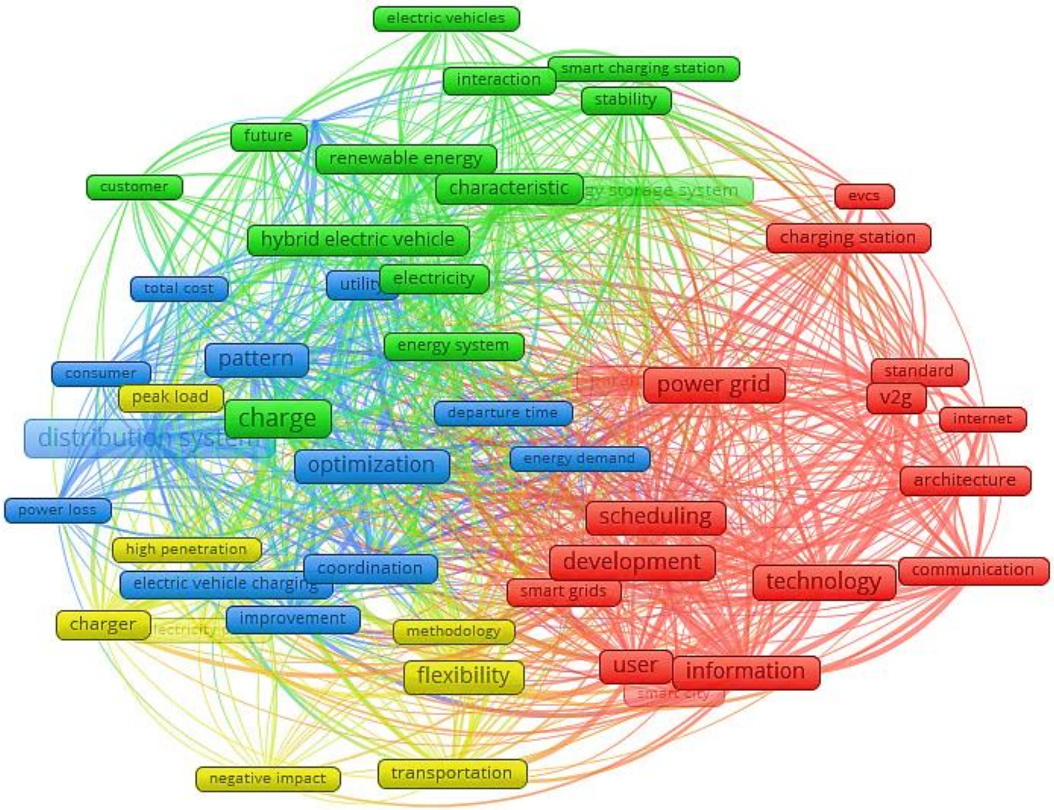

Fig. 2. Most frequent keywords in the previous works regarding EVSC.

This paper is continued as follows: Section 2 is related to the EV aggregator and its role in EVSC. The charging methods are outlined in the next section. Section 4 discusses the potential of EVs in providing ancillary services. The EVs' load forecasting is focused on in Section 5. Section 6 is related to smart charging objectives deployed in previous works. Different EV penetrated energy systems are discussed in the next section. Section 8 deals with smart green charging of EVs using renewable energy systems as an effective action to enhance the positive environmental impact of EVs. The corresponding infrastructures (enabling technologies), including the charger and ICTs, are focused on in the next section. The respective challenges for implementing EVSC are reviewed in Section 10. Finally, the paper is concluded in the last section.

2. Role of electric vehicle aggregator in smart charging

Aggregators are intermediate for-profit entities [51] between the power system and the end-users to enable distributed generations and responsive loads to provide electricity services appropriately to improve the flexibility of the power grid [52]. For instance, direct control of end-user appliances like air-conditioning systems in critical conditions such as peak-demand emergency conditions is one of the tasks of the aggregator [53]. Aggregators can have pros for both the power grid and end-users in addition to their incomes from energy aggregation [54]. Aggregators are also responsible for setting up needed technologies such as communication, measurement, and control devices [55]. So, the aggregator is an entity managing various distributed generation resources or different types of flexible loads to provide ancillary services for the power network by participating in day-ahead and intraday electricity markets under related energy bids [56].

In the literature on power systems, different types of aggregators have been defined, such as retail aggregator, demand response aggregator, generation aggregator [57], and EV aggregator [58]. In this study, the focus is on the EV aggregators. The EV aggregator is defined as an interface entity that aggregates the EVs to act as dispersed energy resources, enabling them to support the V2G mechanism [59]. In another definition, the EV aggregator is responsible for power providing and charge/discharge controlling of EVs under its contracted area [60]. In another study [61], the EV aggregator has been defined as a central coordinator who manages the battery SoC level of geographically distributed EVs. EVs formed a virtual storage capacity to meet EV users' mobility needs and offer energy and regulation services to the grid. Each aggregator manages a certain number of EVs, which is seen as flexible power demand or an energy storage unit [62]. Based on another reference, EV aggregators try to maximize the profit by conducting the EVs charging in low-demand hours, and participating in ancillary services markets, particularly in high-demand hours [60]. Developing/implementing charging infrastructures and providing charging services have been mentioned in another study as the tasks of the EV aggregator [63]. Generally, the EV aggregator brings benefits to itself, EV owners, and the power network [64].

An EV aggregator is subjected to various challenges, such as the minimum required SoC level of EVs [65], power supply reliability [12], uncertainty in electricity market price [66], provision of reserve and regulation power of EVs, etc., without compromising the satisfaction level of EV owners [67]. An EV aggregator has two different aims in the wholesale-side market and client-side retail market [68]. On the wholesale side, there is a competition between EV aggregators against other demand-side market participants for optimal electricity purchases and procuring ancillary services. In the client-side retail market, the aggregators contribute to end-users against other agents which provide similar products and services. The schematic diagram regarding the role of aggregators in EVSC is depicted in Fig. 3 [69].

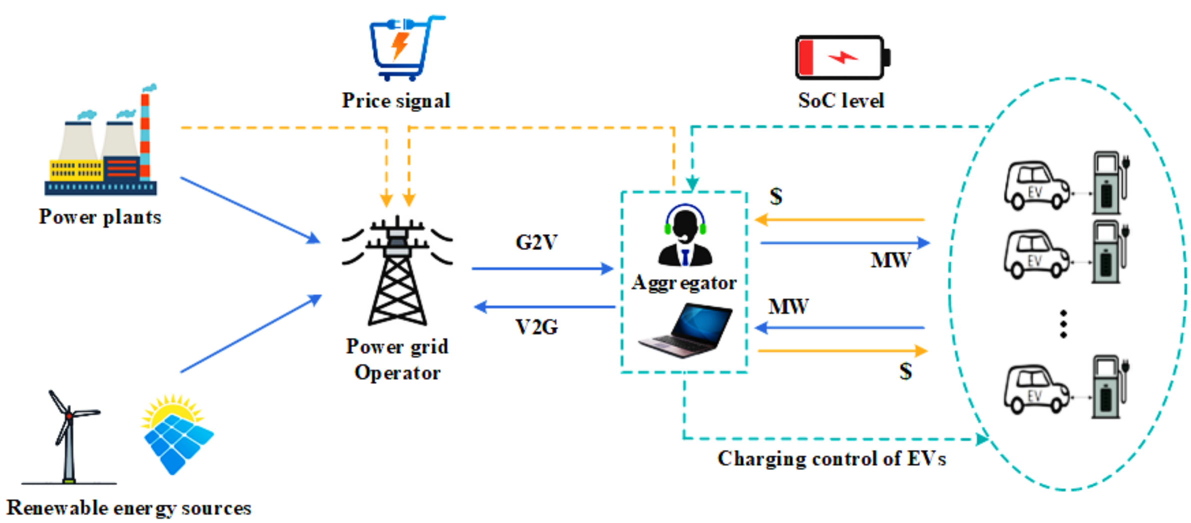

Fig. 3. Role of EV aggregator in electric vehicles smart charging.

3. Electric vehicle types and charging methods

There are different types of EVs, in which their single energy source or one of their energy sources is electricity (from the battery or on-site generation of electricity) [70]. Battery electric vehicles (BEVs) or so-called all-electric vehicles, only-electric vehicles, or pure electric vehicles, are fully powered by a battery with no secondary energy source. BEVs have no emissions; however, the electricity used to charge them may come from dirty (fossil) fuels, such as electricity production in coal-fired power stations. Another type of EV, namely hybrid EV (HEV), is fed from both the battery and a secondary source (such as petrol, diesel, or gas fuels). HEV has not the capability of connecting to the power grid for battery charging.

In such vehicles, the battery is charged through the internal combustion engine. For this reason, the battery in these vehicles is not very large in capacity. Plug-in hybrid EV (PHEV) as another type of EV is the improved version of HEV, i.e., PHEV has the capability of connecting to the power grid for battery charging. Therefore, in PHEVs, the battery can charge from the internal combustion engine or the power grid. In using PHEV, battery usage is preferred for daily travel rather than the secondary source (due to environmental and maintenance considerations). However, BEV has a higher priority to be charged in parking lots or charging stations since it has a single energy source (i.e., battery). The limited mileage of EVs (due to the limited capacity of batteries), and a low number of public charging stations, have led to the development of PHEVs because of their additional energy source. However, two-thirds of existing EVs are BEVs, and battery technologies are developing to enhance their energy density [1].

There is another EV type, i.e., fuel cell EV (FCEV) or so-called hydrogen EV, in which the fuel in such vehicles is hydrogen [71]. In FCEV, the hydrogen is converted to electricity through an electro-chemical reaction. The schematic diagram of different EV types is illustrated in Fig. 4, which includes HEV, PHEV, BEV [72], and FCEV [73]. The power and energy density of fuel cells compared to electrical energy storage systems is depicted in Fig. 5 [74]. As this figure shows, a fuel cell has a low power density, whereas its energy density is high; making it suitable for vehicles. In addition, hydrogen as a fuel for FCEV

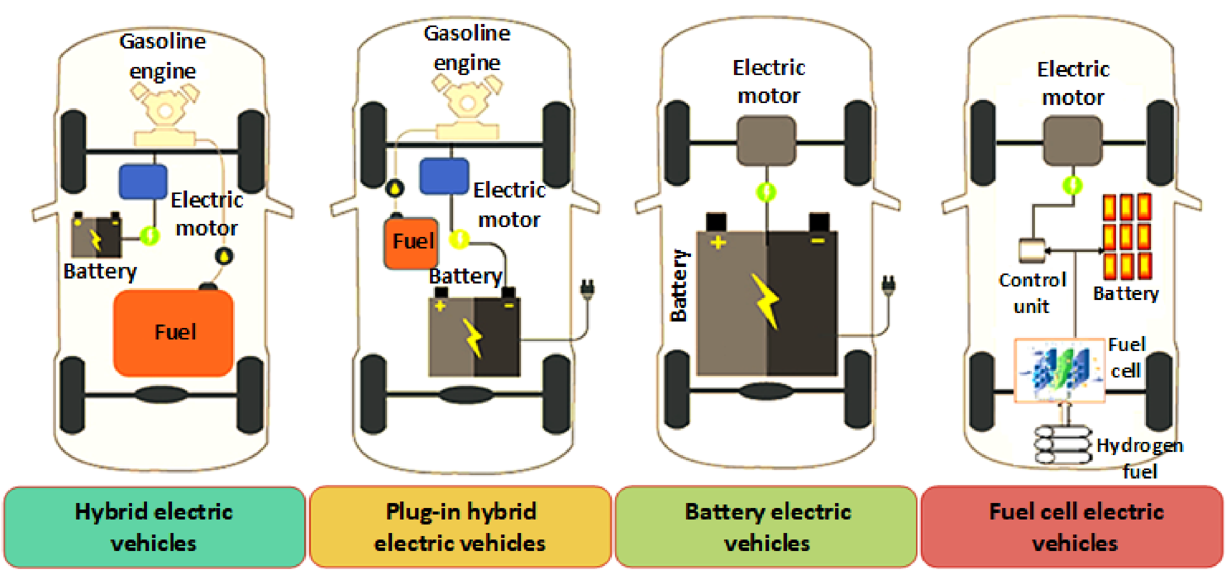

Fig. 4. Schematic diagrams for different types of electric vehicles.

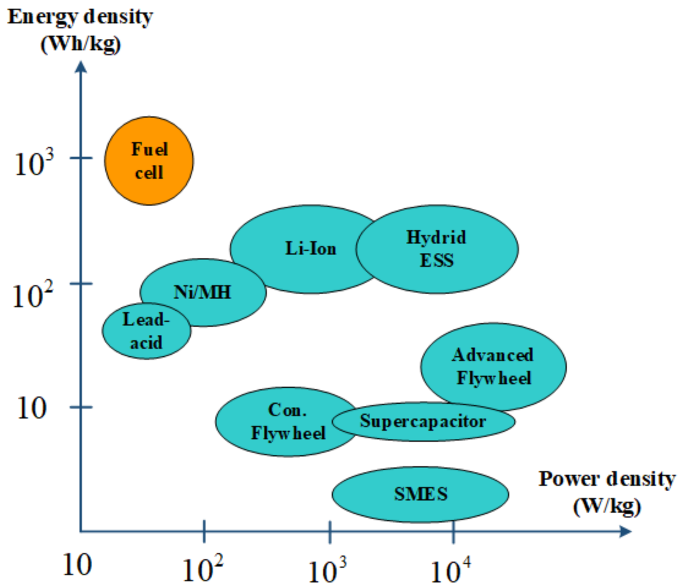

Fig. 5. Power and energy density of fuel cell compared to energy storage systems.

is clean that can meet environmental considerations similar to BEVs. The additional power of renewable energy sources can be turned into hydrogen [75] and used to recharge FCEVs when required [76].

There are different methods for daily charging of EVs. The most common way for charging EVs is through homes and buildings' parking lots [77]. This charging method is mainly accomplished at night when EV owners usually do not need their vehicles at this time. Public parking and charging stations are deemed an alternative option where EV charging is mainly accomplished during the day and in shorter periods [41]. There are two charging station types; regular AC charging stations and DC fast-charging stations [78]. Replacement of the EV battery in battery swapping/switching stations is another way to supply the EVs' energy needs. In this method, the empty battery of EVs is replaced with a fully-charged one in a short time [79]. The energy needed for EVs can also be supplied through energy exchange among EVs [31]. These vehicles in such a V2G recharging mechanism will be known as "user vehicle" and "charger vehicle", respectively [80]. This service is proper for EV owners who value time more than extra payment for charging the battery. In summary, there are several methods to meet the energy demand of EVs, including homes, parking lots (building's parking or public parking), charging stations, and battery swapping/switching stations, as presented in Fig. 6. In Fig. 7, the EVs' charging duration with respect to different values of DC fast charging power levels is shown [78].

As mentioned, one of the charging locations (particularly during the day) is charging stations. Based on a study, smart charging for a station led to a considerable cost saving (for the demand charge) per month compared to uncoordinated charging [81]. The charging start time in such stations depends on the number of EVs in the queue (in case of traffic congestion in the station), location of the daily route of EV from the charging station, charging tariffs (i.e., the electricity price corresponding to the EVs charging) in the related period, and charging power rate [1]. The location-routing problem of these stations is optimized based on the maximum usage (or so-called the "utilization rate" of the charging station (the central operator of the stations tries to maximize this rate) [1] as well as minimum parking issues, traffic, and stress on the power network [82]. However, population density is the primary factor in determining the location of both regular AC and fast DC charging stations [82]. Intra-route facilities are another criterion to enhance the "utilization

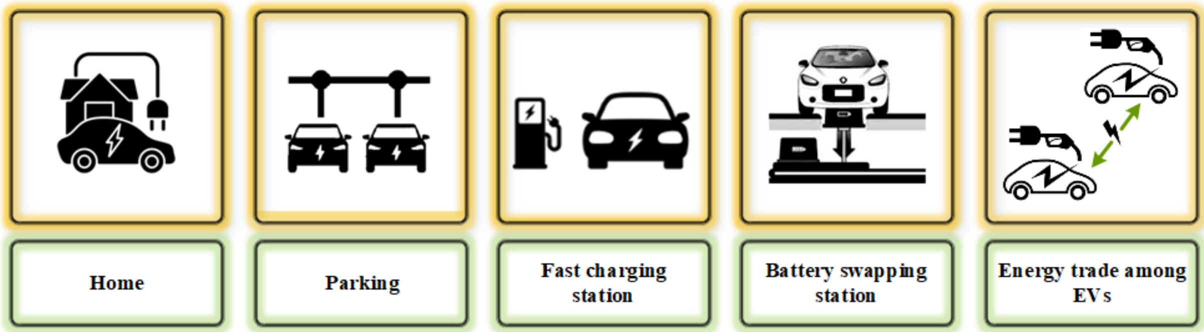

Fig. 6. Existing methods for electric vehicles' smart charging.

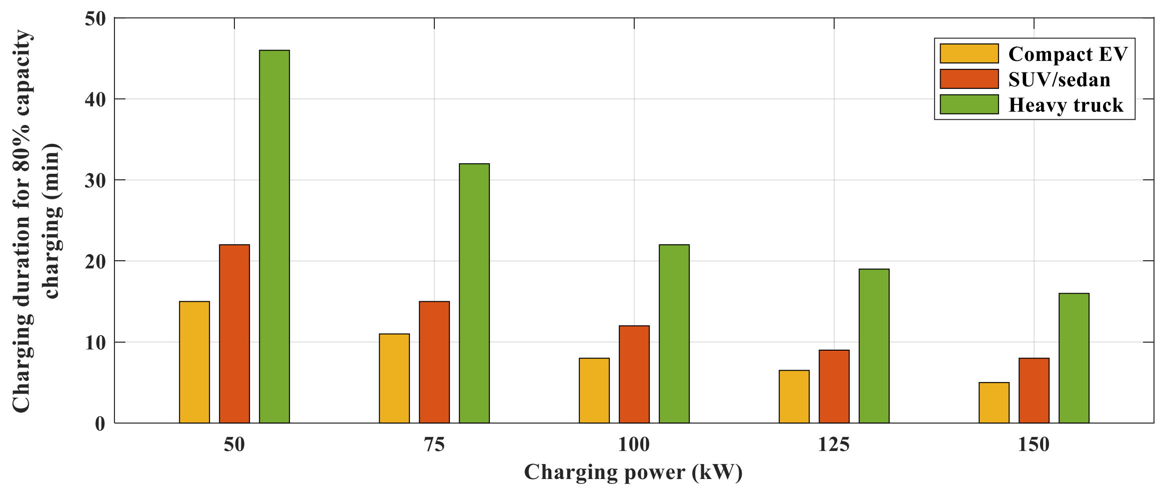

Fig. 7. Charging duration of EVs with respect to the charging power of the DC fast charger.

rate" of such stations [1]. Some probable locations for locating charging stations are the parking lots of the markets, medical complexes, airports, schools, universities, factories, highways, etc.

A charging mechanism comprises different parts, including EVs, charging stations, networking platforms, back-end service centers, payment gateways, and charging applications (which are needed for charging and payment) [83]. There are four charging strategies in EVSC, including constant voltage, constant current, the combination of constant voltage and constant current, and constant power strategies. Table 1 presents the advantage and functions of each method [40].

4. Smart green charging

Charging EVs using renewable energy sources or so-called green charging has attracted the attention of researchers due to environmental considerations and the interest in the closure of fossil-based plants. In this regard, variable renewable energy sources have been more focused than other renewable sources due to nearly zero operation costs (zero production cost and a low O&M cost) of variable sources [84]. By

Table 1. Charging strategies and related characteristics.

Charging strategy	Aim (Advantage)	Function
Constant voltage	Highest battery lifetime	A constant voltage is applied at the terminal of the battery and the current drawn depends on the internal impedance and the voltage difference
Constant current	Rapid charging	A constant current is applied, in which the charging duration is reduced by applying larger currents
Combination of constant voltage and constant current	Most simple charging (popular strategy)	EVs are firstly charged with constant current mode up to a threshold SoC level, and then the charging mode is changed to constant voltage
Constant power charging and multistage current charging	Optimum thermal performance	The power or current in the charging process is controlled to achieve the optimum thermal performance of the battery

integrating EVs with variable renewable sources, in addition to supplying EVs' load with clean energies, the uncertainty in such energy sources (namely solar panels and wind turbines) can be mitigated, e.g., through absorbing the surplus energy of variable sources, particularly in low-demand hours [85].

In this section, the integration of EVSC with both non-variable and variable renewable sources is discussed. In [86], green charging has been achieved by integrating a 20 kW charging station with biogas resources. Compared to the grid-based charging station, the proposed biogas-based charging station could save 65.61% carbon emission. The lifetime and payback periods of the proposed topology were 10 and 5 years, respectively. In another study [87], feasibility evaluation of biogas- and solar-based charging stations integrated with battery storage to minimize the stress on the power network has been studied for a case in Bangladesh. The results indicated that the proposed system could reduce carbon emission by 34.68% compared to the grid-based charging station.

The optimal size and location of solar-based charging stations in a metropolitan area have been investigated in [88]. The energy demand for EVs, investment cost, and uncertainty in the generation of solar panels were taken into account in this reference. In [89], a scheme has been introduced for the optimal scheduling of decentralized solar-assisted charging stations. The maximum capacity of stations, as well as minimum queue delay for charging EVs, were considered in this reference. By deploying the proposed EVSC strategy, the charging time was reduced by 10%. Furthermore, to enhance the usage of solar power, the integration of rooftop solar panels with EVs has been focused on in [90]. Moreover, the on-the-road solar energy harvesting method for smart charging of solar PHEVs has been studied in another work to reduce the charging cost of PHEVs [91].

The possible sites for establishing wind-assisted charging stations in a wide area have been investigated in [92], considering the wind potential of the intended sites. To distribute the charging demand of EVs in the power network, the authors in [93] have integrated charging stations with wind turbines.

Moreover, in [94], the potential of different wind turbine types as a direct energy source to power charging stations has been evaluated.

Integration of charging stations with both solar photovoltaic panels and wind turbines contributes to more improvement in the environment and economic aspects of charging stations. In [95], EVs have been integrated with solar photovoltaic panels and wind turbines in a stand-alone system. The results showed that 12,780 kg/day carbon reduction could be achieved by using the proposed topology for EVSC. In addition, the application of HOMER software for sizing solar-wind-assisted charging stations has been focused on in another study [96].

5. Smart charging objectives

Different objective functions have been studied in the literature for EVSC. For each objective function, the mentioned constraints corresponding to EVs and the power grid must be taken into account. Fig. 8 illustrates the potential objectives of EVSC strategies. In [12], the objective functions have been defined as the minimization of lost load by considering the loss of load expectation as well as expected energy not supplied indexes. The authors in [97], have considered the profit maximization of the EV aggregator, as the objective function, of participation in the flexible ramping product market. Furthermore, profit maximization of a smart parking lot integrated with a wind turbine, combined heat and power unit, and power and energy storage systems has been investigated in [98]. In another work [99], the authors have investigated the total operational costs minimization of a microgrid including EV charging station, solar photovoltaic, and battery storage system, in which the operational costs were related to the bidirectional energy exchange cost (purchase and sell), the wearing cost for charging/discharging of storage systems, and costs related to EVs. On the other hand, the EV-related costs included the cost of the EV charging, the revenue for EV discharge, and the wearing cost of batteries for both charging and discharging. Moreover, in [100], the voltage stability due to the increased penetration of EVs has been mitigated in a renewable-

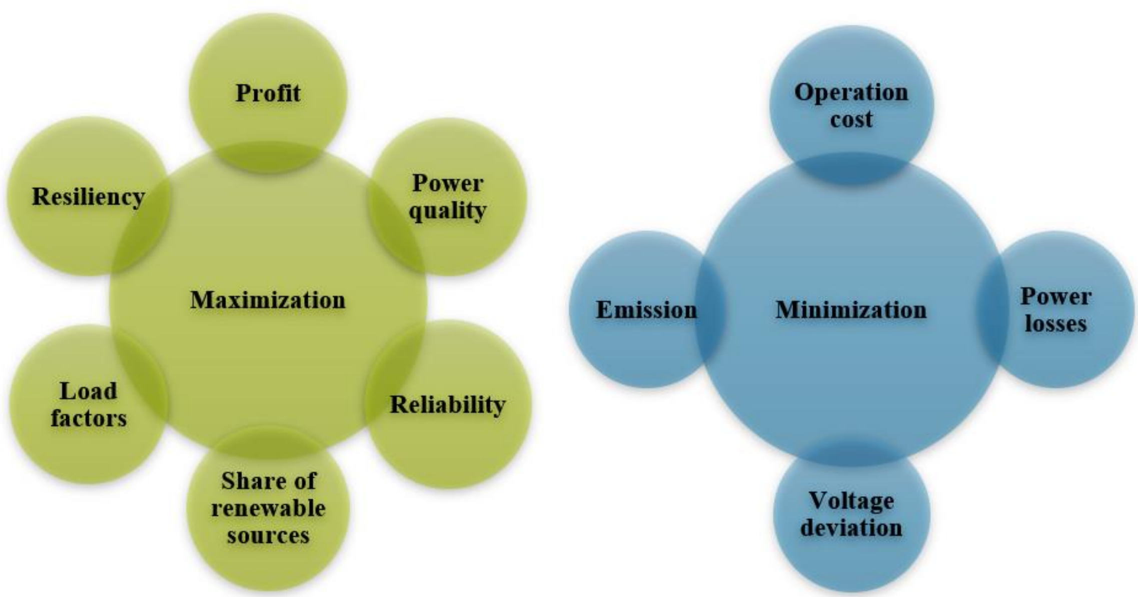

Fig. 8. Objective functions for electric vehicles smart charging procedures.

integrated microgrid via a robust model based on minimizing operation and investment costs for parking lots, solar panels, and wind turbines.

Maximizing the share of the solar photovoltaic system through EVSC in a parking lot has been targeted in another research [101]. Voltage deviation minimization from a nominal value has been considered the objective function of EVSC in another research work [102], in which the active and reactive power losses were also reduced by improving the voltage profile compared to the base case (i.e., the absence of EVs). Emission reduction of microgrids using EVs integrated with demand response programs has been studied by a number of other researchers [103]. The authors in [104] have focused on a multi-objective model for smart charging of EVs based on minimum cost and emission in renewable-integrated microgrids. Moreover, load factor maximization via EVSC has been investigated in another research work [105].

In the literature, various benefits have been mentioned for EVSC. The effectiveness of EVSC in reducing charging costs for a case in Europe (including Belgium and Germany) by 15–30% and decreasing CO_2 emissions by 600,000 tonnes per year by 2030 compared to unmanaged charging has been mentioned in [106]. This reference has also mentioned the influence of EVSC in reducing renewable curtailment in California by 40% and the power grid operational costs by 10% by 2025.

6. Ancillary services offered by electric vehicles to the power system

The EVSC procedures have been developed to overcome several issues related to EVs' stochastic charging, such as voltage regulation, power loss, power quality, peak load, load factor, reliability, stability, flexibility, and phase balance [42]. However, the number of under-charging EVs, EV types (all-electric, hybrid, or fuel cell EVs), the capacity of batteries, charging time, and the required SoC level of the EV owners are the influencing factors on the quality and type of services offered by EVSC procedure to the power grid. In this context, ancillary services are referred to as a variety set of supportive services (provided by relatively small energy resources and flexible loads) that could improve electricity transportation's stability, efficiency, and reliability. Such services preserve desired power flow and related direction of electricity inside a distribution or transmission power network, support power imbalances between the demand and supply sides, and contribute to the system recovery after a failure or event. In Fig. 9, the types of ancillary services that can be provided by EVSC are depicted. For example, procurement of peak load reduction and voltage regulation services by EVSCs have been studied in [12] by optimizing two reliability indexes (i.e., the loss of load expectation and expected energy not supplied indexes). In [107], the potential of EVs for providing 10% of the peak load of New York City with 50% penetration of EVs has been reported, showing a cost-saving equal to $110 million per year. Peak load shifting has been focused on in another study [108] for a grid-connected EV parking lot integrated with solar panels. In another research [109], resilience improvement of a household customer in the aftermath of a hurricane by deploying PHEVs has been accomplished, in which various load profiles for different consumption scenarios were generated to assess the resiliency against the severity of the conditions. In the same work, PHEVs cover the household load for a reasonable time during the power outage.

In [110], a focus has been given to the potential of EVs for loss minimization in distribution systems. The results showed that load factor minimization is approximately equivalent to energy loss minimization. Still, it is independent of the system topology, which is more appropriate from the viewpoint of computation burden rather than directly minimizing system losses. Congestion management in distribution systems using EVs has been investigated in some other research studies for load relieving on transformers and feeders [111] as well as distribution lines [112]. In [113], the impacts of the increased penetration of EVs

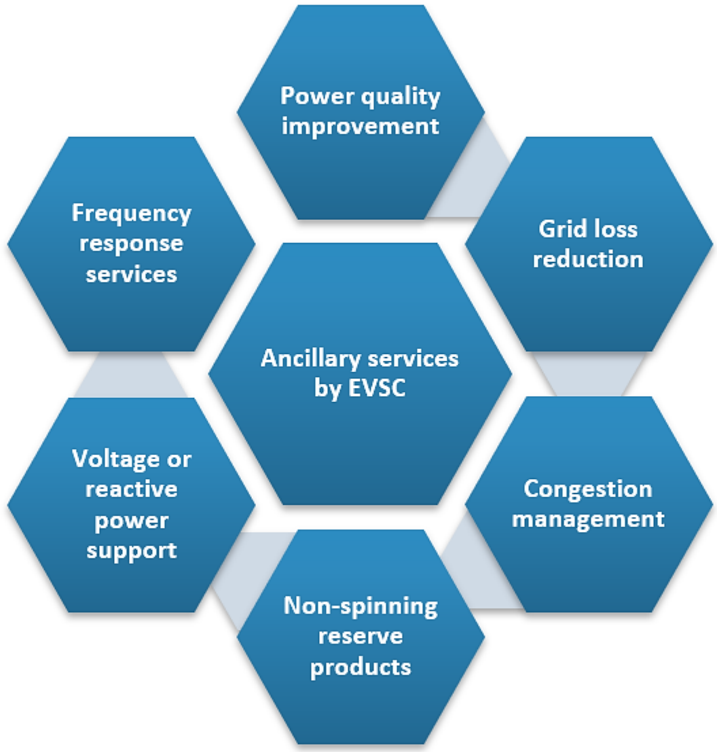

Fig. 9. Ancillary services that can be provided by electric vehicles smart charging.

on congestion of the German power system have been discussed and their mitigation plans through decentralized ancillary services which in turn reduce the need for conventional redispatch of power plants have been proposed followed by a number of recommendations.

In [114], the authors have improved the power grid transient stability and robustness using V2G when the system is faced with significant disturbances, such as generator and line tripping, and sudden considerable changes in the system load. EVSC improves the voltage fluctuation and critical clearing time by 80% and 20–40%, respectively. In another study [115], the authors have investigated the improvement of the voltage imbalance factor in distribution systems by optimizing the state of EVs (charging/discharging), the point and phase of connection of EVs, and the charging/discharging rating power. The results showed a significant improvement in the voltage imbalance by deploying an EVSC strategy for a set of coordinated plug-in EVs. Moreover, in [116], transformer loading, voltage profile, and current imbalance in unbalanced distribution systems have been controlled using EVSC. In another research, the load factor and voltage fluctuation have been improved using EVSC [117]. The results indicated that by the participation of EVs in the electricity market, the optimal number of EVs (i.e., the fleet size handling capability) is increased. The results also showed that by deploying EVSC to retain the system characteristics at a reasonable level, a greater number of EVs (e.g., four times) can be handled compared to the stochastic charging of EVs. In [118], harmonic compensation of a distribution network has been accomplished by EVSC based on a robust optimization method considering economic and technical objectives. The economic objective included EVs' revenue and energy cost, and the technical objective included the voltage deviation and total harmonic distortion (THD). In the related literature, EVs have also been considered a means of active and reactive power support in distribution systems [119].

Moreover, some other studies have focused on adopting EVSC for primary [120] and secondary [121] frequency regulation of power systems. EVs can also participate in tertiary frequency regulation based on economic dispatch [49]. Primary frequency control is expected to benefit more from V2G than the secondary and tertiary frequency control.

7. Electric vehicle-penetrated energy systems

EVs have an important role in future power networks since they act as both energy consumers and producers, called prosumers [122]. Using power electronics devices, intelligent grid connection, and interactive charger control, EVs can be seen as mobile energy storage resources [15]. EVs can also be integrated into energy systems supporting both stand-alone and grid-connected applications. Connecting local networks to the main grid shows their ability to exchange energy, which is important for improving the economic operation of such local networks by smart charging/discharging of EVs.

The presence of EVs is also important in renewable-based energy systems. In such systems, EVs can absorb the surplus energy of renewable energy sources and use it later for daily travel or energy arbitrage in a green and cost-effective way. For integrating EVs into an energy system, the consideration of the understudy network from the viewpoint of energy sources for charging EVs should be assessed. The EVs' electricity demand could be supplied from the main grid or by distributed energy sources (including renewable energy sources and non-renewable energy resources). This point is illustrated in Fig. 10.

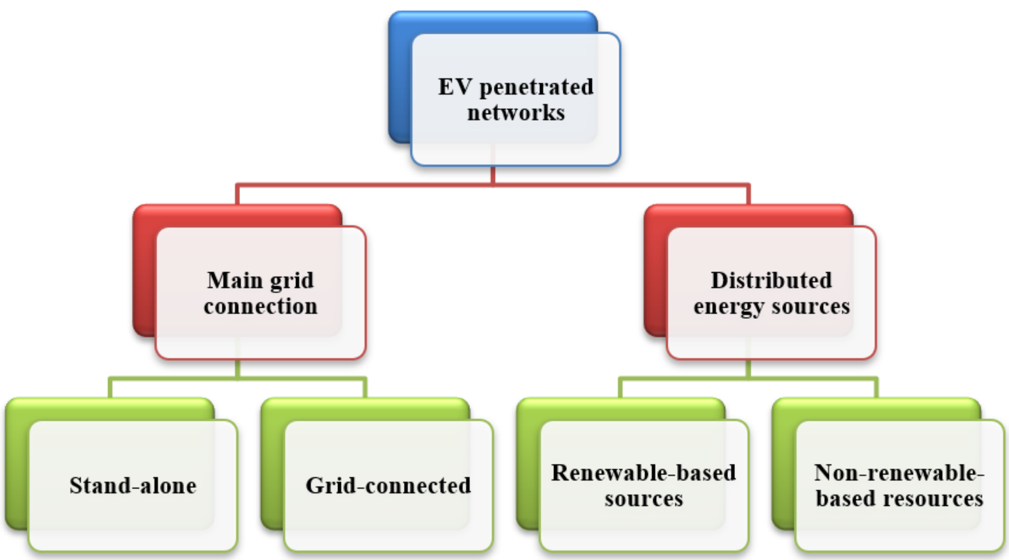

Fig. 10. Categorization of EV penetrated power networks from the viewpoint of grid connectivity and availability of renewable energy sources.

EVSC is conducted in different energy systems for smart charging/discharging. Buildings are fundamental for V2G since it hosts most EVs during the night (i.e. peak load time). EVs can also connect to distribution systems through charging stations or public parking lots. In Fig. 11, different EV penetrated power networks are shown. In the following, the integration of EVs with such systems for EVSC is discussed:

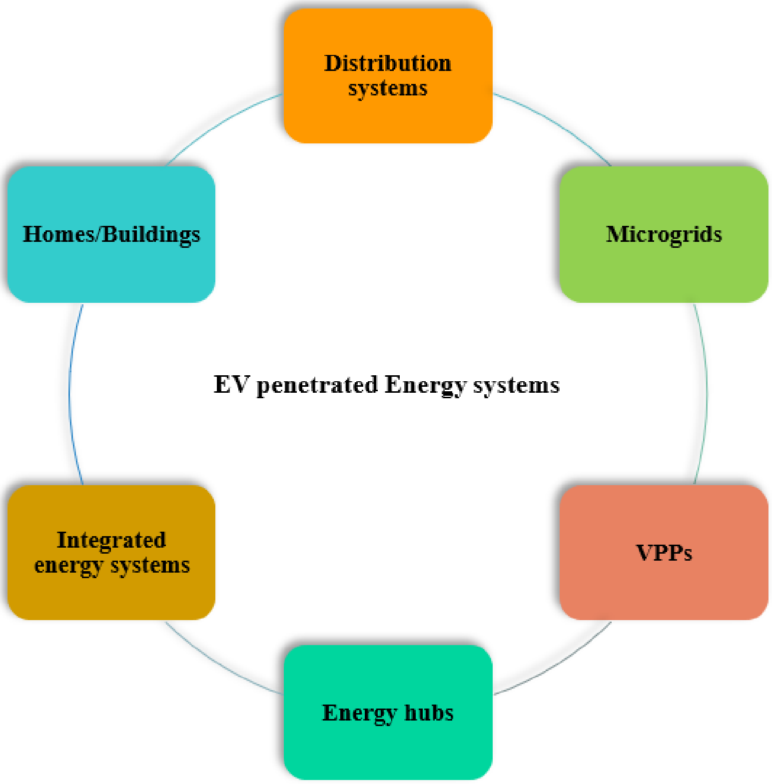

Fig. 11. Electric vehicle penetrated energy systems.

Home/Building: Within upcoming years, many EVs will be interconnected with homes or buildings to be charged through the main grid or distributed generation systems. In [123], EVs have been integrated with a cluster of homes equipped with wind turbine, combined heat and power (CHP), boiler, and electrical and thermal storage for cost-saving through optimal energy management. In another study [124], PHEVs, as well as solar photovoltaics, are combined with buildings to provide higher flexibility in operation and lower energy consumption costs. In another research [125], the integration of EVs and solar photovoltaics has been taken into account as responsive components of a building to peak load mitigation as well as profit maximization. Vehicle-to-building has been integrated with a photovoltaic/battery system for peak load reduction in [126]. Furthermore, in [127], a hybrid photovoltaic/EVs/battery system is integrated with an office building considering the uncertainty in the driving pattern of EVs and photovoltaic generation. Moreover, in [128], demand-side management of commercial buildings has been conducted with related components, including EVs, heating, ventilation, and air-conditioning (called HVAC) systems, and electric water heaters.

Distribution system: Due to the fast-growing trend in green transportation, distribution systems will host many EVs in the future. In [129], parking lots with high penetration of EVs are integrated with distribution systems. A load aggregator is in charge of direct participation of parking in the retail power market. In another research work [130], EV parking lots benefit from selective participation in both price-based and incentive-based demand-side response programs in distribution systems. In the same study, the impact of different participation percentages of the understudied parking lot in such demand-side response programs has been outlined on the daily profit. Furthermore, in [12], EVs have been integrated with off-grid distribution systems for bidirectional smart charging with the aim of reliability improvement, in which the understudied system was integrated with distributed generation units. The authors in [131] have investigated to minimize the harmonic distortion caused by large-scale EV penetration in the distribution system. Moreover, in [132], EV and solar photovoltaic are integrated with real-time optimization of the reactive power of the distribution system to improve the operational costs, power losses, and voltage profile. The siting and sizing problem of a distribution system operator owning EV parking lots has been planned in another study in [133] to maximize the profit of distribution companies. Finally, the optimal placement of fast-charging stations in the distribution system has been investigated in another research [134] for improving the power losses as well as voltage deviation.

Microgrid: Microgrids are stand-alone or grid-connected electricity grids which are optimized for generation adequacy or profit from energy exchange with the main grids. Microgrids can support EVs for smart charging considering economic and reliability aspects. In [135], incentives are paid to the EV owners to participate in demand response programs of renewable-based microgrids. Day-ahead scheduling of microgrids, including EVs, renewable sources, energy storage, fuel cell, microturbine, and distributed generators, has been studied in [136] to cost minimization, in which several charging/discharging patterns of EVs were considered. The authors in [137] have investigated the generation scheduling and feeder reconfiguration of a microgrid, including EVs and different distributed generation units. Furthermore, in [138], the integration of EVs with renewable-based microgrids in both stand-alone and grid-connected modes has been studied to minimize the operational costs, which contained the profit of EV owners. Moreover, EV parking lot, hydrogen refueling station, fuel cell, wind farm, and solar photovoltaic plant have been integrated with combined heat, power, and hydrogen microgrid in another study [139] to meet the electricity and thermal loads. Moreover, in [140], optimal design of a hybrid islanded system, including EV parking lot, battery storage, and renewable energy sources, is accomplished based on minimizing construction and operating costs as well as emission level of the system considering various uncertainties. The results outlined the effect of the EV parking lot in decreasing the installation cost of stationary battery storage systems.

Virtual power plant: VPP is a decentralized network that coordinates a large and varied range of distributed energy resources in a large geographic area and can participate in the wholesale electricity market [141]. In a VPP, A bunch of EVs, as large-scale battery storage, not only can receive needed energy for daily travel, but they can also improve the economic operation of VPPs. In [142], EVs are integrated with VPPs, including renewable energy sources and demand response programs to minimize the total operational costs of the system considering the uncertainties involved in the scheduling phase. Improving the frequency response of VPP using EVs has been focused on in [143]. In another study [144], EVs have contributed to regulating the power reserve of VPPs. Cost and emission reduction of an EV penetrated VPP from the viewpoint of consumers has been studied in another research [145]. The integration of EVs and wind turbines has been considered in another research to act as VPP [146]. The authors in [147] have studied the integration of EVs and photovoltaic system with VPP to minimize the social utility loss during a long-term period. Moreover, smart charging/discharging of EVs has been considered in [148] for improving the carbon emission of VPPs.

Energy hubs (multi-carrier energy systems): Energy hubs, or so-called multi-carrier energy systems, are capable of energy production, conversion, and storage. Penetration of EVs in energy hubs needs suitable energy management schemes since this penetration may upset the balance of the demand in such systems. The impact of EV penetration on energy management of energy hubs has been studied in [149]. The authors in [150] have investigated the minimization of the purchase cost and emission tax cost of an energy hub integrated with EVs and energy storage. In another study [151], energy management of a residential energy hub integrated with EVs and solar systems (solar photovoltaic and solar collector), has been accomplished with the aim of operational costs minimization, in which flexible power and thermal loads have been considered. In [152], EVs, fuel cells, hydrogen tanks, and renewable energy sources have been integrated with an energy hub related to a smart commercial building, where seawater desalination units were considered flexible loads. Moreover, in [153], electricity, thermal, and cooling loads have been considered as load demands of an energy hub, including EVs, combined heat and power units, and electrical, thermal, and cooling storage.

Integrated Energy Systems: Penetration of EVs is important in systems with every combination of power, gas, and heat networks since the changes in the electricity load, change the operation of energy conversion systems, such as CHP systems, gas-fired generators, boilers, etc. EVs as energy storages (which play the role of non-coupling technologies in integrated energy systems) [154] can be effective in such systems for balancing supply and demand. EVs and renewable sources have been integrated with combined power and gas networks in [155]. In the same work, the role of EVs and gas-fired generators in increasing the share of renewable sources has been outlined, especially the role of gas-fired generators in enhancing the interdependency between natural gas and electricity networks. In another research [156], a residential charging station has been integrated with an integrated power and gas network, including hydrogen storage, CHP, gas-fired unit, non-gas-fired unit, and renewable sources. In this reference, EVs were only charged and could not discharge. Another research [157] has studied EV charging in integrated power distribution and transportation networks. In [158], the integration of EVs with a microgrid, including several buildings with space heating, cooling, and electrical loads, has been studied. Moreover, in [159], the presence of EVs in integrated power and district heat systems has been discussed.

8. Forecasting the electric vehicles' charging load

Load forecasting of EVs is fundamental for EVSC, which is in charge of optimizing the number of EVs, charging/discharging rate, and charging locations considering the grid characteristics. In addition, forecasting the EVs' load helps a better economic dispatch of existing energy sources to supply the power grid load [160]. The daily driving patterns (driving distance and arrival/departure time), EV type, day of week and season [161], the penetration rate of EVs [162], etc., are influential factors on the load profile of EVs in a specific geographic area. In Table 2, the data sources and mechanisms needed for parameters forecasting in EVSC are depicted [36]. As this table shows, data handling mechanisms include clustering, forecasting, and scheduling.

There are various methods to predict the load profile of EVs. Such methods forecast the EVs' load using historical driving/traffic data for fifty-five electric taxis in Beijing [163] and an Industrial zone in Iran [164]. In another study [165], the Monte Carlo simulation has been adopted to forecast the EVs' load by considering the EV types, charging mode, charging period, daily mileage, and charging power, whereas the number of EVs was forecasted by using the Bass model. The authors in [166] have introduced a hierarchical method to predict the EVs' load profile. Firstly, at low-level regions, the problem is decomposed into sub-problems, which are resolved via probabilistic models, including the quantile regression forests, gradient boosted regression trees, and quantile regression neural networks. Then, an ensemble methodology based on a penalized linear quantile regression model is deployed to forecast the aggregate load of EVs for the high-level geographic area. Time-series models have been studied in another study to predict the EVs' load [167]. The obtained results showed that separate prediction of EVs' load (by considering the EV type, SoC level, drive pattern of owners, and destination) instead of overall prediction of the EV fleet tends to the improved prediction of EVs' load. The studies have focused on the nation, city, and single charging station by deploying actual measured data. In [168], to overcome the uncertainty in EV charging load in

Table 2 Data sources required for electric vehicles' smart charging.

Scheduling data	Clustering data	Forecasting data
• **Demand side**	• **Pre-process**	• **Survey**
- Distribution network Transformers	- Select	• **Smart metering**
- Transmission lines	- Merge	
- Circuit breaker	- Clean	
- Load demand profile	- Formation	
- Large-scale case studies such as city, state, and the entire nation		
- Small-scale case studies such as university campuses, small cities, shopping mall	• **Data mining**	
	- Clustering	
• **Charging Profile**	- Correction	
- Driving pattern	- Clean	
- Driving behavior	- Regression	
- Type of vehicle		
- Battery size		
- State of charge (SoC)		
- State of health (SoH)		
- Spatial and temporal		
- Connection time		
- Disconnect time		
- Charging station ID		
- EV ID		

reconfigurable microgrids due to the charging strategy, numbers of under-charged EVs, charging duration, and charging start time, a deep learning-based predicting method, namely the gated recurrent units technique, has been deployed. Moreover, in [169], the non-intrusive extraction of EVs' load has been accomplished using an LSTM deep learning algorithm to predict the charging load.

In [170], a model based on a generalized regression neural network, as a machine learning technique, has been introduced to predict the traveling behavior and arrival/departure time of EVs to form the EVs' load profile. In [171], a reinforcement learning-based method, i.e., the Q-learning technique based on the recurrent neural network and ANN, has been employed to forecast the EVs' load. The results showed that the Q-learning technique has lower forecast error than the recurrent neural network and ANN. Furthermore, in [160], an ensemble learning-based predicting method has been deployed to predict the load of EV charging stations. In the proposed method, three learner algorithms, namely the long short-term memory

(LSTM), recurrent neural network (RNN), and artificial neural network (ANN) algorithms, were combined. The weighting of each base learner was based on a linear regression method. In another study [172], the comparison among three neural network-based methods for predicting the EVS' load profile has been accomplished. The findings indicated that the results of Multilayer Perceptron Training, as well as Jordan Education methods, are favorable, whereas the Radial Basis Function method has a higher error and computation burden for EV's load prediction. In [173], six different deep learning approaches have been compared from the viewpoint of EV load forecasting. The methods included ANN, RNN, canonical LSTM, gated recurrent units, stacked auto-encoders, and bi-directional LSTM forecasting methods.

9. Required infrastructure for smart charging

For implementing EVSC, complementary technologies related to the charger infrastructure and ICT are required. The EV aggregator has to set up these infrastructures. Currently, the role of the policymaker is crucial in developing the required infrastructure for EVSC by providing the required subsidy to ease access to enabling technologies.

9.1. Charger

Chargers may be situated inside the EV (on-board charger) or located outside the EV (off-board charger) [174]. The on-board chargers are deployed for low-power AC charging, whereas the off-board chargers are used for high-power AC charging and DC charging [175]. From the viewpoint of charge direction, there are two unidirectional or bidirectional charger types [21]. The second one is needed for providing ancillary services by EVSC. However, the security issue and its higher cost are barriers to developing bidirectional chargers. From the viewpoint of the charging process, there are two charger types, namely wired (conductive) [45] and wireless (inductive/contactless) [46] chargers. Regular wired charging is accomplished through alternating current (AC) charging mode as well as direct current (DC) charging mode. The characteristics of different charging levels are illustrated in Fig. 12 [46]. As this figure shows, different voltage, current, and power levels are deployed for EV charging. The application of different charging levels based on charging locations is depicted in Fig. 13 [176].

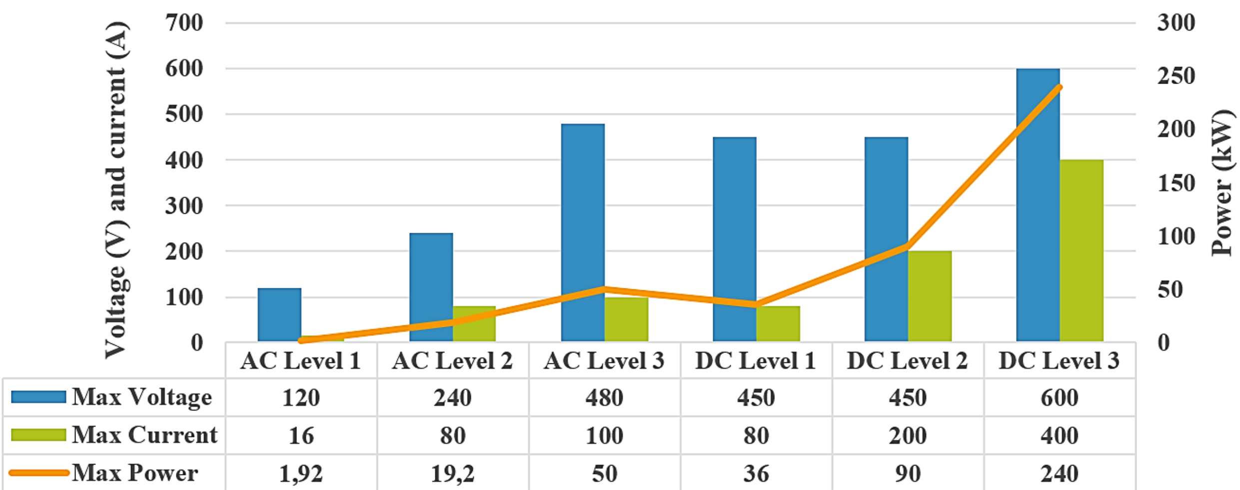

Fig. 12. Comparison of different charging levels from the viewpoints of voltage, current, and power.

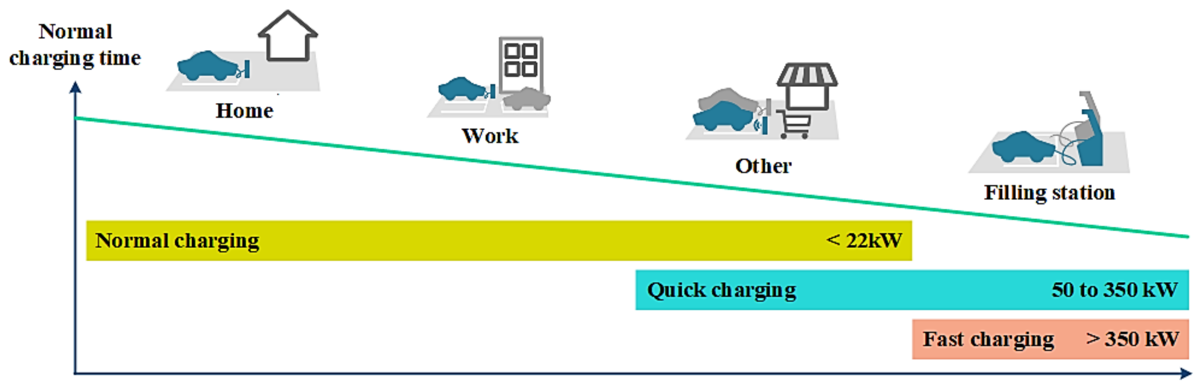

Fig. 13. Schematic diagram for charging power and time with related charging locations.

There are two AC charger types; AC slow charger and AC fast charger. The first requires a single-phase supply, whereas the second requires a three-phase supply [23]. Although the regular power networks are based on AC power, the research shows that DC power increases the charging operation of EVs and considerably reduces the charging time [177]. DC power can be provided by converting the AC power to the DC one at the location or supplying the charging power from stand-alone DC microgrids. Therefore, the current charging stations are mainly DC-based and operate based on the three-phase four-wire system [83]. However, as a minor limitation, DC fast-charging stations need a larger charging cable size (due to the higher value of current) than AC charging stations [23]. DC power for EV charging is provided by power electronic converters [178]. DC charging stations have three core elements, including a charge controller, tariff and control unit, and insulation detection module, as shown in Fig. 14 [83]. As mentioned

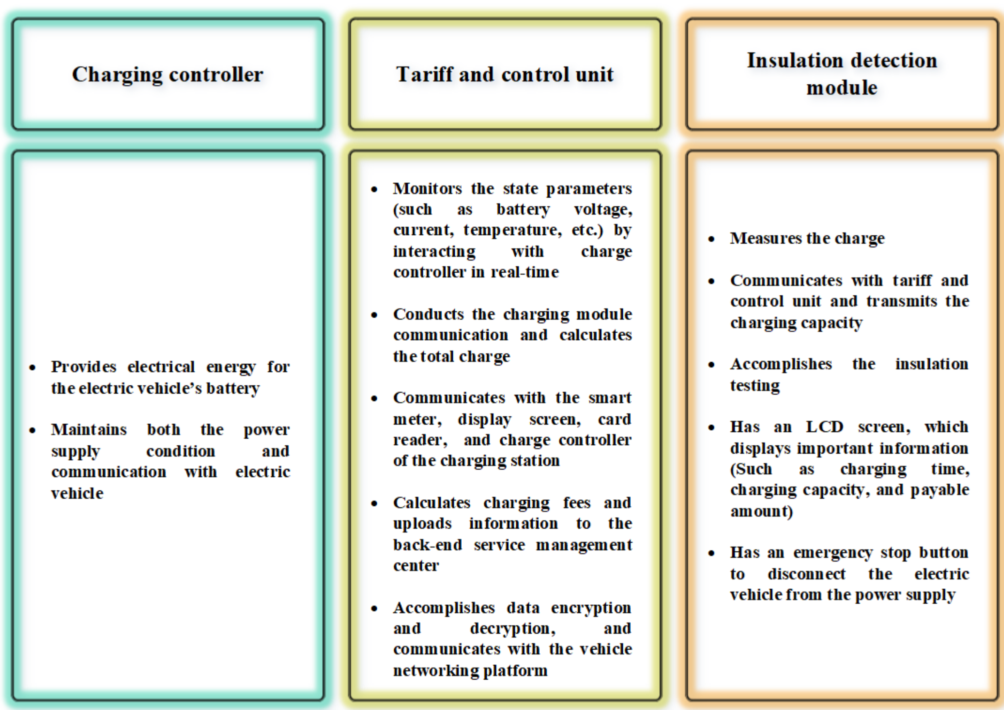

Fig. 14. Core components of DC charging systems.

earlier, the charging stations are mainly DC charging stations rather than AC ones due to the lower time needed for charging EVs in such stations.

9.1.1. Wireless charger

Although commercially available EVs use the cable to create the V2G system (i.e., wired charging), wireless V2G chargers are an alternative for wired chargers to overcome the challenges of wired charging. The corresponding challenges, including the vandalism and safety issues, are because of the open contacts and hanging charging cables in public areas [179]. However, like wired charging, wireless charging needs safety considerations [180].

Wireless charging procedures (or so-called contactless charging [181]) are divided into static and dynamic charging methods. In static wireless charging, the EV owner should park the EV at a charger access point (and leave it) for battery charging, whereas dynamic charging is related to EV charging when EVs are moving [44]. Dynamic charging is also called "roadway powered", ''on-line", or ''in-motion" wireless charging [46]. The dynamic charging method needs road electrification. There are some technical and economic challenges to dynamic charging of EVs, such as finite energy transfer distance, stability limit of the power system (especially during peak load periods), the high investment cost of such infrastructure, and also safety, reliability, and efficiency issues [1]. The enabling technologies of EVSC, including the charger types and ICT with respective subcategories, are illustrated in Fig. 15 [46]. Fig. 16 shows the charging methods and related strategies [46].

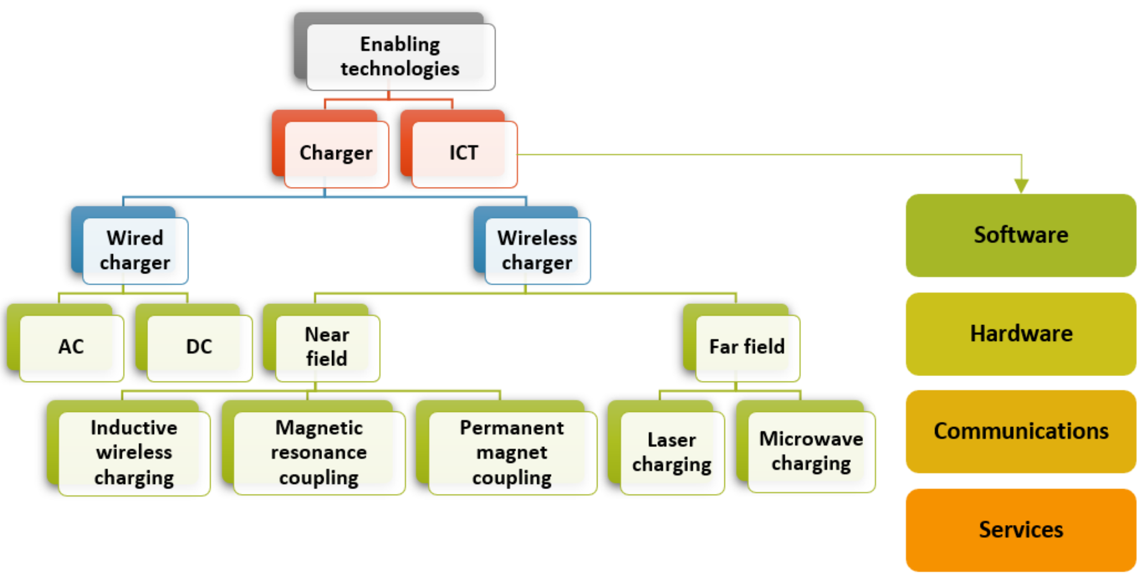

Fig. 15. Infrastructure (enabling technologies) required for implementing electric vehicles smart charging.

9.2. Information and communication technology

ICT is the other enabling technology for implementing EVSC by remote monitoring and controlling for battery charging, finding the nearest charging point, charging tariffs of charging stations, real-time

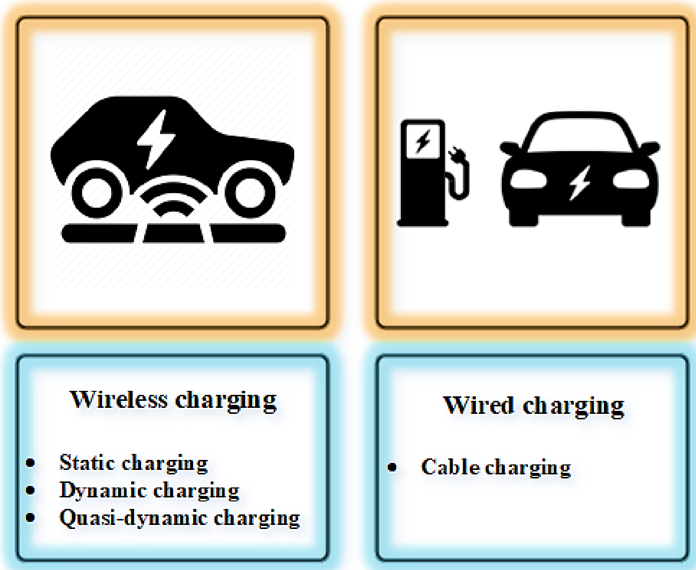

Fig. 16. Strategies for wireless charging of EVs.

consideration of the grid characteristics, etc., [182]. Although the ICT concept first appeared in the 1940s, still a determined definition does not exist for this concept [183]. ICT allows the EV aggregator to access, store, modify, and transmit information from one place to another faster, more conveniently, and easier [182] by using related equipment such as cell phones, wireless networks, and the internet. The ICT tools include software, hardware, services, and communications. An EVSC communication system should be devised to deliver information efficiently and reliably [182]. The electricity price, SoC level, driving pattern, nearest charging location, etc., are considered in the communication system of EVSC infrastructure. Internet of Thing technology, as a novel ICT form (from 2009), is a developed form of radio-frequency identification technology (from the 1980s) and wireless sensor networks (from the 1990s) [184]. The most promising Internet of Things (IoT)-based enabling technologies for EVSC are Radio Frequency Identification (RFID), Ultra High Frequency (UHF), and Wireless Sensor Network (WSN) [185]. For enabling EVSC to use ICT, a hybrid sensing network, smart gateway, cloud services, and mobile applications are required [185].

Innovative and sophisticated approaches/tools are also needed to process the Big Data generated from the stakeholders [186]. For future connected vehicles, Vehicle-to-Infrastructure (so-called V2I) communication is required to facilitate the EVs for accessing the Internet via innovative technologies in mobile communications, such as Bluetooth, WiFi, 4G, and even 5G networks [187]. Data losses and delays in communication systems are inevitable in using ICT for the EVSC mechanism. Considerable losses and delays can degrade the system performance [188]. The global positioning system (GPS) is also beneficial for increasing the charging opportunity during the day or at travel stops by finding the charging stations [189]. For the integration of the charging station or parking lot with the power network, Fiber-optics are effective due to their reliable and high-speed nature [190]. However, wireless networks are more critical for EVSC. In this regard, as a novel technology, Vehicular Ad-Hoc Networking (called VANET) is effective for EVSC communications [190].

Implementing an EVSC system needs different considerations, such as the information system, EVSC battery management system, sensors, physical system, and EV owners (driver). The information system includes a communication interface, data storage, mobile app, and control algorithm [191]. Based on the studies, four major components are involved in developing EVSC: the research and consultancy, the policy side, the energy market, and the charging infrastructure market [192].

10. Challenges

There are different challenges in implementing EVSC. In general, the EVSC challenges include the battery depreciation cost, the needed intensive communication between the EVs and the power network, infrastructure changes, charging impact on power distribution network facilities, and also security, social, political, cultural, and technical barriers [15]. In general, technological, economic, and social aspects should be considered in EVSC. These aspects along with corresponding subcategories, are depicted in Table 3 [30].

Table 3. Challenges involved with electric vehicles' smart charging.

Technological	Economic	Social
• Charging time • Degree of standardization • Influence of battery • Local grid impact	• Energy cost • Energy management • Initial and installation cost • Operation cost • Revenue possibilities	• Ease of use • Safety

10.1. Grid-related challenges

One of the main impediments in this regard is the needed electric power to meet the energy demand of EVs with the increasing number of EVs, particularly in peak demand hours [193]. The production of this additional power may lead to frequent dispatch of costly generators (such as gas turbines), thus, increasing the power network's operational costs. In addition, the EVs charging process, as an additional load imposed on the current power network, may lead to issues, particularly at lower voltage levels. One implication may be congestion of lines and transformers (this issue intensifies especially in heavily populated areas, where the electricity grid has no free capacity to meet additional loads) [194]. Other implications may be power losses [195], power quality issues [196], harmonic distortion [197], voltage drop and imbalance [198], peak load, poor load factor, thermal stress [199], frequency deviations [200], voltage instability [201], reliability deterioration [202], decreased resiliency [203], etc. The studies for the Belgium grid showed that 30% EV penetration would result in 10% increases in peak demand [15]. Such negative impacts decrease the useful lifespan of power network facilities such as transformers [15].

In a bulk power network, the V2G infrastructure cannot promptly and frequently receive large-scale electricity injections without considering the aspects such as the electricity market, power network operation control, and demand-side response management [43].

Although the charging/discharging power is the only influential factor on the power grid, the SoC level indirectly impacts the charging/discharging power; thus, the network characteristics are affected [204]. A sample for this issue is illustrated in Fig. 17 for voltage THD concerning the SoC level [204]. As this figure shows, the SoC level impacts the network characteristics and should be considered especially for dynamic problems (of the power network) rather than static problems.

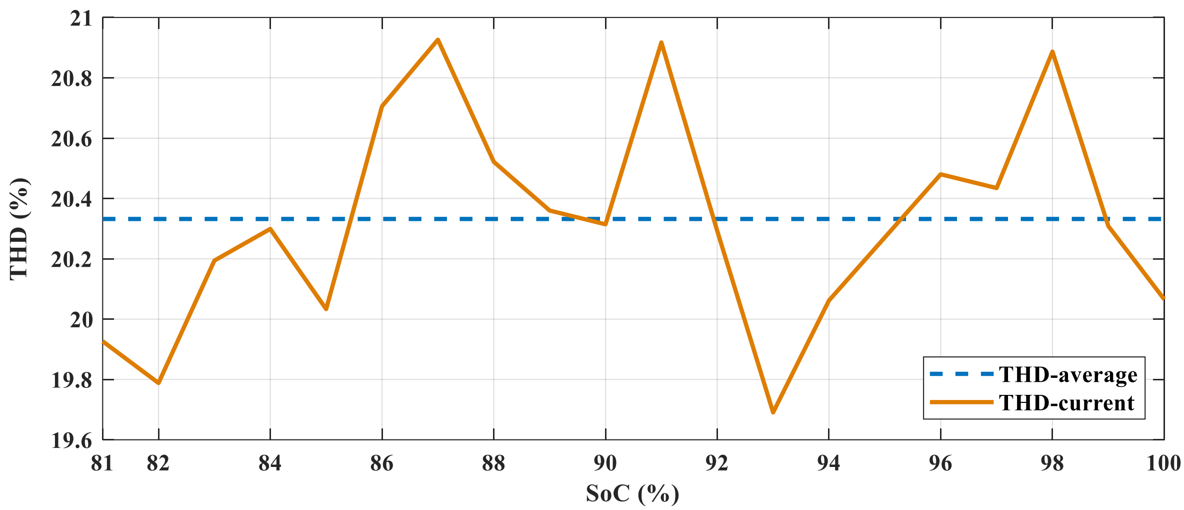

Fig. 17. Changes of harmonic distortion with respect to the SoC level for a typical problem.

The investment cost for software and hardware infrastructure is another grid-related challenge in implementing V2G. However, charge infrastructures are involved with energy conversion systems, and the charge/discharge of a large fleet of EVs leads to a considerable energy loss in the power system, which is another challenge in this regard [205].

10.2. Bidirectional power flow challenge

Another barrier is that the present distribution networks have not been designed for bidirectional power flow; this leads to a limit on the service capabilities of the EVSC mechanism [15]. The conventional protection systems are not suitable for reverse power; thus, they may not respond to them. With the growth of EVs, power electronic converters are required for managing the bidirectional power flow [40]. This challenge can also be solved by using the discharging power of EVs at the location to supply local loads.

10.3. Grid reinforcement challenge

The EVSC procedure should overcome such challenges either directly or indirectly; otherwise, additional investments in overhead lines, underground cables, and transformer capacity are needed to meet the extra load of the power network [15]. In other words, the increased penetration of EVs needs the power grid upgrade without an EVSC mechanism [1]. For instance, by installing distributed generators like renewable energy sources to power the charging stations, the power network congestion (caused by the increased penetration of EVs) is solved [23]. For another instance, to solve the voltage drop, reactive power compensation approaches can be adopted [206].

10.4. Pricing mechanism challenge

The presence of EVs in electricity markets leads to diversification in such markets and provides new economic opportunities [21]. However, like other small-scale energy providers, two barriers exist to the participation of V2G in electricity markets. These barriers include the least acceptable bid size (which needs large-scale aggregation), particularly at the early stages of implementing V2G, as well as the complexity of managing a lot of EVs compared to a large power provider [207]. Effective market mechanisms motivate the willingness-to-participate of EVs with the minimum incentive to be paid to EV users [208]. The type of electricity market and related market mechanisms for V2G considerably affect the economic operation of EVs. However, the penetration level of EVs is also effective on the pricing mechanism [209]. For EVs' load to shift to low-demand hours as far as possible, an appropriate pricing mechanism is needed to motivate EV users and enhance their willingness-to-participate level. In such price-based schemes, the power price in low-demand hours is significantly reduced to encourage customers to charge their EVs at these time intervals rather than the peak hours [48]. Therefore, pricing policies/mechanisms of electricity for integration of EVSC with electricity markets is another barrier [5].

In electricity markets, three different pricing methods, including fixed tariff, dynamic tariff, and demand response tariff, exist for EV charging, load-leveling, and frequency regulation [210]. Dynamic tariffs for EV charging are based on the spot price of electricity. In fixed tariffs, a lower fixed price is determined for EV charging via the wholescale market. Demand response tariffs present an opportunity for EV users to discharge their EVs for providing ancillary services in exchange for a benefit. Among these three pricing mechanisms, the dynamic pricing of electricity is the most complex form of pricing [48]. In this pricing type, the charging price per unit of electricity varies with time and is not specified before the charging process; thus, the total charging cost is not specified in advance. Dynamic pricing schemes are conducted to enhance the users' flexibility by managing their behavior in using electricity [48].

Estimating the discharging cost of EVs for ancillary services in demand response tariffs is another challenge in implementing EVSC [211]. The EV owners may not be pleased to inject their EV's energy into the grid [43]. However, studies have shown that by the participation of EVs in ancillary services, significant benefits (e.g., up to 9,600 €/year) can be achieved for EV owners by offering certain regulation services [15]. EVs can participate in different electricity markets, including the energy market [212], capacity market [213], and ancillary services market [214] through day-ahead, intra-day, and balancing markets [215].

10.5. Battery degradation challenge

Battery degradation caused by EV discharging (when EVs provide ancillary services) and fast charging is another challenge for EVSC. As a result of degradation, the battery shows higher resistance; thus, the battery life is reduced. Low temperatures and high SoC levels are two factors for increasing this resistance. Charging EVs via fast charging options leads to battery degradation on a long-term basis [23]. As a solution, using the battery swapping station is a better option for EV recharging. Discharge depth and cycling frequency are two factors that could accelerate battery degradation and negatively affect its state of health [15]. Retaining the SoC level at a middle level (about 50%) maintains the battery life from premature depreciation [15]. Estimating the cost of battery degradation for discharging is difficult since the battery technologies are still developing [15]. Currently, Li-ion batteries with an investment cost of \$200–\$500 per kWh are the most promising option for EVSC because of their high efficiency, high energy density, reasonable deep-cycling capability (2000–4000 deep cycles), and long life. An initial battery cost of \$300/kWh with a lifetime of 3000 cycles for an 80% discharge depth leads to a battery depreciation cost of \$130/MWh [15]. Another option is to retain the monetary value of EVs battery by its utilization for stationary applications in buildings after replacing the battery [216].

10.6. Optimal location of charging stations

Another challenge in developing EVSC is establishing an accessible and reliable charging infrastructure for EV owners [217]. In this regard, optimizing the location of constructing the charging station is a challenge [218]. The respective location should be selected in such a way that the profit of the charging station owner is maximized. Faster charging speed is a solution for charging station owners to make the station attractive to EV owners. The charging station owners can also make the station attractive for EV owners to enhance the station's profit [219]. Avoiding on-site congestion to prevent long queues of EVs in the charging station is another challenge that needs the station upgrade to be matched the load demand of the station.

10.7. Battery swapping challenges

There are some impediments to developing the battery swapping method. Firstly, the growth of this method needs the standardization of batteries [1]. In addition, the initial capital cost for constructing battery swapping/switching stations is much higher than fast-charging stations [78]. These two barriers exist to the growth of battery swapping stations.

Another hindrance in developing EVSC is the existence of various charging levels [23]. The protocol standardization is effective for faster growth of charging stations and more acceptability of EVs [180]. In this regard, some aspects, such as the rated power of charging, communication, and safety, should be standardized [23]. A standard charging method has to optimally meet the user's needs and cover the highest safety requirements [180]. Three major pillars of standardization in EVSC are compatibility, performance, and safety, as presented in Fig. 18 [220].

10.8. Needed space for installing charging equipment

Another barrier is related to the current homes/buildings, which may have no specific space for installing the smart charging equipment. The future homes/buildings will adapt to this requirement, but the current homes/buildings have to assign a specific space to the EV charging infrastructure [23].

10.9. Low capacity of batteries

The high charging cost of the EV battery, long charging period, and lower traveling distance of EVs with a full battery than conventional vehicles are the other challenges for growing EVSC [23]. These could be of great importance for EV owners, especially on trips and long-distance travel [80]. However, the weight of EVs (components and cables) is decreasing, effectively reducing the energy consumption of EVs. The improvement in energy consumption may also be attained by replacing the induction motor of EVs with a brushless DC motor or even a switched reluctance motor. In addition, the novel charging technologies (with 50 kW from the DC source) can deliver the required charge in half an hour [80]. However, the demand for the fast charging station is an important challenge for the power network [80]. In the case of needing emergency charge when charging locations do not exist, energy exchange among EVs is a solution [31].

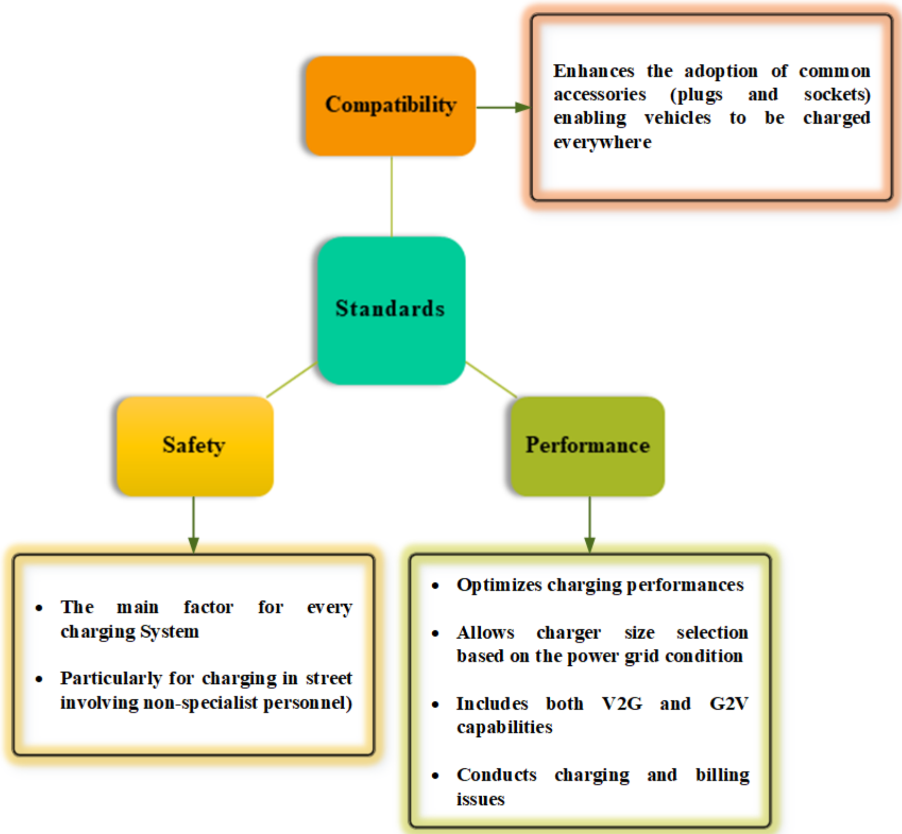

Fig. 18. Three main pillars of standardization in EVSC.

Wireless V2G recharging mode has been studied in the literature to drive further distances without stopping [80]. However, the efficiency of contactless charging for moving vehicles is lower than common wired charging because of the larger air gaps [5].

10.10. Security challenge

Privacy and security are becoming increasingly prominent issues for EVSC problems. The communication procedure in EVSC includes a wide range of information that may be accessed by an attacker. The information includes billing data, tariff information, SoC level, etc., [83]. Cyber-attacks on smart charging infrastructure are conducted with different aims, such as tempering/forging charging data for billing loss, preventing the power supply of EVs, and sealing charging information for disclosing the charging account and corresponding location [83]. Therefore, attackers through cyber-physical systems can interfere with the charging process and threaten both charging stations and the user's privacy. The lack of a robust charging system leads the users to be tricked/deceived, and believe the fake SoC level. For instance, the attacker may send the stop message to the charging station to show the SoC level of 100%, while the EV is not fully charged [83]. The lack of authentication mechanisms in the subscriber identity module (SIM) cards when dialing into the access point name (APN) enhances the probability of hacking the charging system by attackers. Currently, researchers are evaluating the ability of Blockchain, as an emerging technology, to provide secure data exchange and messages in peer-to-peer EVSC against cyber and physical threats [221]. This technology is being successfully implemented for IoT and the financial aspect of EVSC. Blockchain can provide a transparent, decentralized, and secure market environment.

A cyber attacker may target one or more parts among five parts of the smart charging infrastructure, including the supply side, charging equipment, cable, on-board charger, or battery management system, as shown in Fig. 19 [47]. Fig. 20(a) shows the potential costs imposed by attacking the charging infrastructure [176]. As this figure shows, in general, cyber costs (system recovery), physical costs (breaking hardware of devices or provoking hazards that endanger the health/life of users), and social costs (exposing the private life of users or decreasing the amount of trust among the customers of a company) may impose to the charging infrastructure. In addition, Fig. 20(b) illustrates the core components of EVSC cyber-security systems, including confidentially (the information be readable only by the valid recipients), integrity (modification can only be feasible by authorized agents), and availability (available when required) [176]. Overcoming a cyber-attack requires several security actions, including identify, protect, detect, respond, and recover. These actions required after cyber-attacks on charging infrastructure are illustrated in Fig. 21 [176].

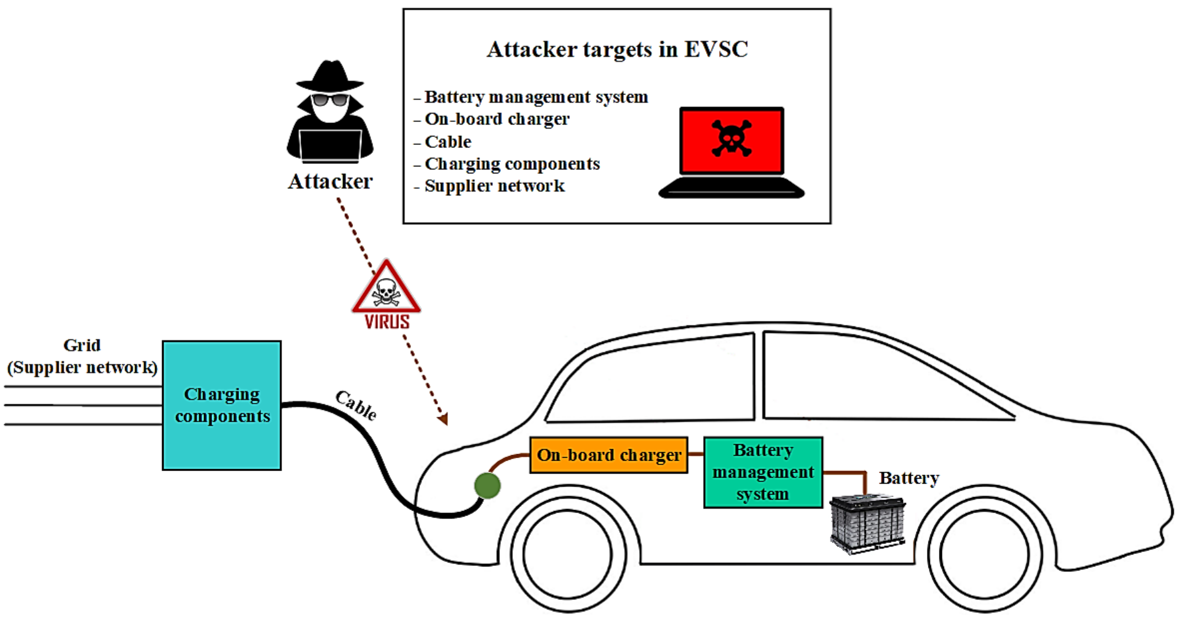

Fig. 19. Potential targets of cyber attackers.

10.11. Uncertainties

Managing the uncertainties associated with EVSC is another challenge. An EVSC strategy should overcome various uncertainties, including the uncertainty in load, grid condition, SoC level, electricity price, generation of distributed generators, etc., [28]. Risk management is an effective method to overcome the uncertainties in EVSC based on information gap decision theory [222], conditional value-at-risk [142], downside risk constraint [223], robust optimization [224], etc. In the following, two main uncertainties related to EVSC, including uncertainty in the availability of EVs and the willingness-to-participate level of EV users in EVSC, are discussed:

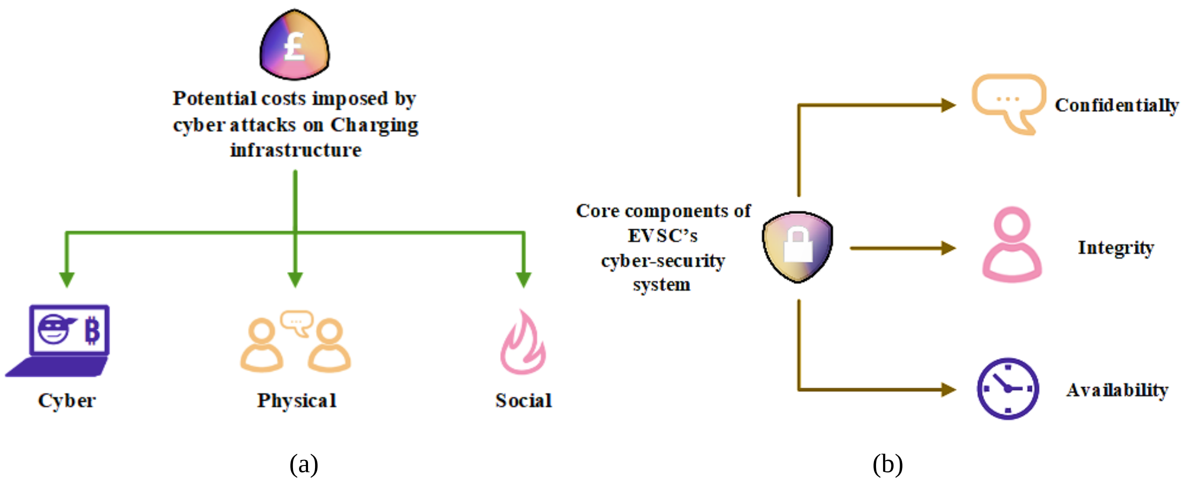

Fig. 20. Imposed costs by cyber incidents and the core components of cyber-security system (a) potential costs imposed by cyber incidents (b) core components of EVSC cyber-security systems.

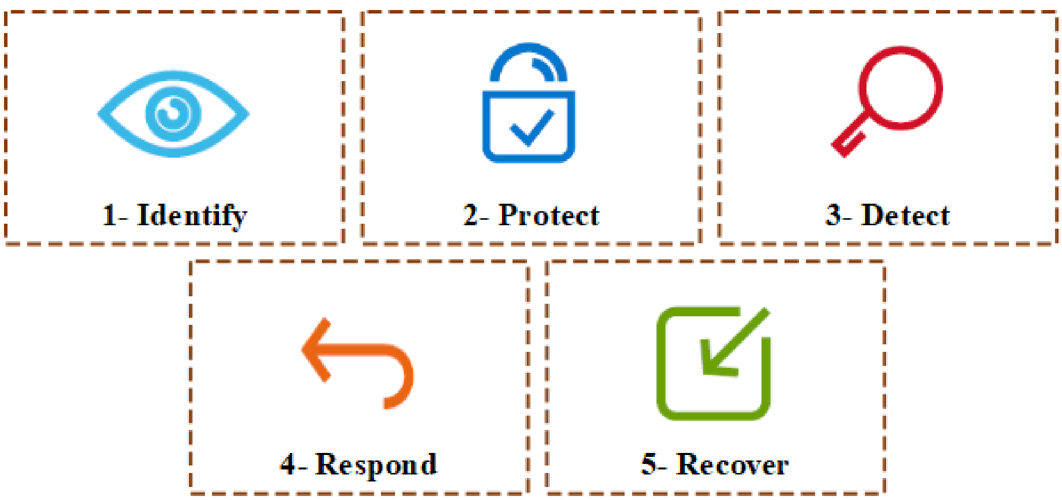

Fig. 21. Required actions after cyber-attacks on charging infrastructure.

10.11.1. Uncertainty in availability of electric vehicles

The uncertainty in the availability of EVs is challenging for EV aggregators to provide ancillary services. The bidding capacity for such services is directly related to the availability of EVs. Plugin-time restrictions and day of the week are effective factors in the availability level of EVs [225]. The research work in [226] has verified that the EV owners may not plug their EVs every day, which impedes the effectiveness of the V2G program. An EV aggregator considers the EV availability uncertainty to improve the contracted bidding; otherwise, the EVs' potential to provide power services cannot be competitive in the electricity market. Various probabilistic methods have been proposed by researchers to overcome this challenge. A Gaussian mixture model based on daily trip data has been proposed in [227], in which the

Copula function was employed to model the interdependency of probabilistic variables. In [228], the availability of EVs has been evaluated based on trip chains. The results showed that homes and offices have the highest availability level of EVs compared to other car parks. In another research [229], a normal distribution has been adopted for the availability of EVs and, consequently, the V2G power. A non-homogeneous semi-Markov process has been employed in another study to model the uncertainty in the availability of EVs [230]. Moreover, in [231], the power and traffic networks have been combined to consider the time-varying availability of EVs for participation in the V2G program.

10.11.2. Uncertainty in willingness-to-participate of electric vehicles

The awareness of EV users of the V2G concept and related programs is a prerequisite for enhancing the willingness-to-participate level of EV users in such programs. The willingness-to-participate level of EVs depends on two factors: concerns (the inconvenience of EV owners from participation in V2G) as well as incentives (revenue from participation in V2G). Therefore, technical and economical designs of the V2G concept are vital to enhancing the willingness-to-participate level of vehicle owners [225]. In [232], it has appeared that EV users are more willing to provide flexibility in the electricity system compared to heat pump users [233]. A fixed monthly premium (namely €15, 30, 45, or 60) and a one-time payment (€1000, 3000, 5000, or 7000) have been mentioned in [225] as incentives to enhance the willingness-to-participate level of EV users. The limiting factors for participation in V2G are divided into permanent or temporary factors from the viewpoint of the EV users. For example, a high driving range in a specific period has a temporary negative impact on the willingness of the related EV user to participate in the V2G program. For another example, the lack of need to profit for a specific EV user is a permanently limited factor for the willingness-to-participate level of that EV user. The conducted research works in this regard show that the profit ranges from a loss of $300 per vehicle per year to a profit of over $4600 [234]. Most studies have revealed a profit in the $100–300 range. The profit from V2G program depends on the V2G objective, such as increasing the share of renewable energy sources in supplying the EV loads, and decreasing the cost of storing electricity in EVs' batteries [235]. The degradation of the EV's battery is another factor that affects the willingness of EV owners to participate in V2G. EV owners may tolerate more levels of discomfort in the V2G program in exchange for receiving a higher profit. Therefore, although two technical and financial factors are effective for designing V2G mechanism, three individual, technical, and financial aspects are effective in the willingness-to-participate level of EVs [225].

11. Real-world vehicle-to-grid cases

The practical V2G implementation includes V2G pilot projects and V2G commercial projects. A V2G mechanism for providing frequency containment reserve service has been successfully implemented in a pilot V2G project, namely the Parker project located in Denmark [236]. The project includes four EV models, including Nissan Evalia, Nissan Leaf, Peugeot iOn, and Mitsubishi Outlander PHEV. In [237], a pilot V2G project has been discussed related to 30 identical EVs owned by the Los Angeles Air Force Base, aiming to minimize the charging cost of the EV fleets and maximize ancillary service revenue by optimizing regulation capacity bids for participation in the day-ahead California frequency regulation market. The used model for this V2G project can minimize the risk associated with uncertainties. In another pilot project, which is part of the Car as Power Plant project located at The Green Village, Netherlands [238], the capability of an FCEV (namely Hyundai ix35 FCEV) in both the mobility as well as power generation has been employed to create a net-zero energy building integrated with solar panels. Two operation models, including fixed power and load-following modes, were considered for FCEV. In a commercial real-world V2G system located in Denmark, namely the commercial Frederiksberg Forsyning EV fleet [239], in addition to timely charging of EVs, the frequency containment reserve service is provided by participating in the Danish frequency regulation market.

There are some other real-world V2G projects, including Clinton Global Initiative School Bus Demo (which is located in the US and provides frequency regulation and load shifting services), Vehicle-to-coffee—The Mobility House (which is located in Germany and provides load shifting), Denmark V2G (which provides frequency regulation service), Powerloop: Domestic V2G Demonstrator Project (which is located in the UK and provides arbitrage and load shifting services) Utrecht V2G charge hubs (which is located in the Netherlands and provides arbitrage service), V2GO (which is located in the UK and provides load shifting, frequency regulation, and arbitrage services), Piha vehicle-to-home (V2H)trial (which is located in New Zealand and provides load shifting service), Namibia V2G (which is located in Namibia and provides load shifting service), and VIGIL (which is located in the UK and provides reserve and load shifting services) [21].

12. Discussion and conclusions

Due to the increasing penetration of EVs, a significant focus has been given to EVSC by researchers in recent years. In this review study, different aspects of EVSC were discussed. The EV aggregator as an entity to enable EV owners for both the timely charging and participation in ancillary services of the power network was first discussed. Different methods of charging EVs and existing strategies for EV charging were reviewed. Ancillary services, load forecasting of EVs, and smart charging objectives were also outlined in this study. Furthermore, coordination of EVSC with different EV penetrated energy systems, including home/building, distribution system, microgrid, VPP, energy hub, and integrated energy systems, were also discussed. Moreover, this review study dealt with smart green charging (as a solution for enhancing the environmental impacts of EVs) and enabling technologies (i.e., charging infrastructure, including the charger and communication technologies). Finally, the corresponding challenges for developing EVSC were outlined. The conducted study revealed that still more research studies and works by researchers and specialists are needed to overcome the current challenges for the growth of charging stations.

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