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Review

System Planning of Grid-Connected Electric Vehicle Charging Stations and Key Technologies: A Review

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Abstract: The optimal planning of electric vehicle (EV) charging stations (ECSs) with advanced control algorithms is very important to accelerate the development of EVs, which is a promising solution to reduce carbon emissions of conventional internal combustion engine vehicles (ICEVs). The large and fluctuant load currents of ECSs can bring negative impacts to both EV-related power converters and power distribution systems if the energy flow is not regulated properly. Recent review papers related to EVs found in open literature have mainly focused on the design of power converter-based chargers and power interfaces, analyses of power quality (PQ) issues, the development of wireless charging techniques, etc. There is currently no review paper that focuses on key technologies in various system configurations, optimal energy management and advanced control issues in practical applications. To compensate for this insufficiency and provide timely research directions, this paper reviews 143 previously published papers related to the aforementioned topics in recent literature including 17 EV-related review papers found in Institute of Electrical and Electronics Engineers (IEEE)/Institution of Engineering and Technology (IET) (IEEE/IET) Electronic Library (IEL) and ScienceDirect OnSite (SDOS) databases. In this paper, existing system configurations, related design methods, algorithms and key technologies for ECSs are systematically reviewed. Based on discussions given in the reviewed papers, the most popular ECS configuration is a hybrid system design that integrates renewable energy (RE)-based power generation (REBPG), various energy storage systems (ESSs), and utility grids. It is noteworthy that the addition of an ESS with properly designed control algorithms can simultaneously buffer the fast, fluctuant power demand during charging, smooth the intermittent power generation of REBPG, and increase the overall efficiency and operating flexibility of ECSs. In addition, verifying the significance of the flexibility and possible profits that portable ESSs provide in ECS networks is a potential research theme in ECS fields, in which the potential applications of portable ESSs in the grid-tied ECSs are numerous and could cover a full technical spectrum.

Keywords: electric vehicle; electric vehicle charging station; renewable energy; energy storage system

1. Introduction

With the continuous growth of environmental concerns, countries around the world have developed various emission standards for carbon dioxide and nitrogen oxides. In this context, electric vehicle (EVs), which mainly rely on electricity, have the opportunity to replace conventional internal combustion engine vehicles (ICEVs) in the near future by utilizing the-state-of-art power electronics, motor drives, energy storage technologies, renewable energy-based power generation, and smart grids; ultimately, they may help decarbonizing the transportation industry. According to the design of energy formation and system composition, EVs can be divided into hybrid EVs (HEVs), plug-in HEVs (PHEVs) and EVs. In recent years, industrial countries have actively developed various economic incentives to further promote EV-related industries and research projects. In fact, EV-related industries and their infrastructures have grown rapidly in the past 10 years. To provide a quick view of the

EV development trend, the global stock evolution of the battery-based EV (BEV) and the plug-in HEV (PHEV) from 2010 to 2016 is shown in Figure 1 [1]. It is clear that the EV market has been rapidly growing and continuously opening up a lot of technical themes for researchers in related fields [1]. Since EVs have gradually become a part of everyday life, the demand for constructing new electric vehicle charging stations (ECSs), also known as EV supply equipment (EVSE), is also expected to increase fast. Adequate ECS planning and operating mechanisms are extremely important to further accelerate the development of EVs and HEVs. To build a modern ECS integrating energy storage systems (ESSs) and renewable energy (RE)-based power generation, some technical issues have to be taken into consideration, e.g., system configuration, power transfer rate, power and energy management, and system optimization [2].

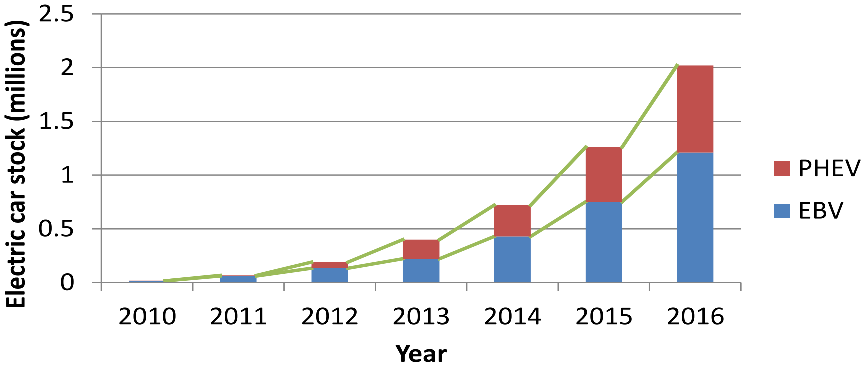

Figure 1. Global stock evolution of electric vehicles (EVs) [1].

Theoretically, the existing system technology of ECSs can be divided into two types according to the way charging power is supplied: (1) A simple grid-tied ECS draws the required charging power completely from the external utility grid. This design may cause a number of power quality problems in the power grid due to the intrinsic operating characteristics of ECSs, such as uncertain peak loads, voltage fluctuations, frequency shifts and short-term overloads, which, in turn, greatly increases system maintenance cost; (2) a grid-tied ECS integrated with renewable energy-based power generation (REBPG) and battery energy storage systems (BESSs) provides charging power mainly stored in ESSs to reduce the impact of instant and irregular high-current charging loads on the grid. In this technology, BESSs can allow for the integration of higher REBPG, which have unpredictable power generation, through real-time power smoothing control schemes. Though both the irregular charging processes of EVs and REBPG are considered adverse dynamic interference sources to the grid, it has been suggested that, with proper coordination control among ECSs, BESSs, and REBPG, ECSs can benefit from carbon-free REBPG systems, and a higher energy efficiency system can be achieved [3]. In the aspect of increasing the energy utilization efficiency and flexibility of EV-related power converters, although single-stage on-board chargers (OBCs) for EVs have the advantages of a small size and a light weight, and it is very desirable to design two-stage or multistage OBCs and adopt wide-bandgap (WBG) switching device-based power converter interfaces to meet the future trends of reducing the power ratings of components, increasing capacities and power densities, improving dynamic performances, and allowing for bidirectional power flow control, also known as vehicle-to-grid (V2G) and grid-to-vehicle (G2V) power flow regulations [4,5]. V2G provides a flexible system operating mechanism in which plug-in EVs or HEVs actively communicate with the power grid to provide demand response services mainly by returning real power. It is important to note that storage capabilities in the V2G system can also enable EVs or HEVs to smooth the fluctuating power flow of REBPG such as photovoltaic (PV) and wind turbine (WT) power generation. However, using EVs or HEVs as grid storage may have a negative impact on battery longevity if the operating current is not properly designed.

V2G technology is usually realized with an alternating current-direct current (AC–DC) power stage for power factor correction (PFC) and a DC–DC power stage for voltage matching. With coordinated charging/discharging and appropriate power management, EVs can be integrated into grids as distributed power sources or ESSs. It is recommended by researchers in this field that the desired features of EV power interfaces include: being compact, reliable, and efficient; having a fast transient response, the ability to charge, low-device stress, low-voltage distortion; and being stable and immune to electromagnetic interference (EMI) [1,5,6]. More recent investigations have indicated that with the integration of state-of-art wireless power transfer (WPT) technology, some advanced ECSs can be realized in the near future [7].

With the fast development of the EV industry, many EV-related research papers have been published [8–143] including subject-oriented EV review articles [8–24]. General technologies for EV, including EV types, energy storage, energy generation, and energy management were reviewed in [8–10]. Various types of EV chargers and charging technologies were reviewed in [11–16]. Various converter topologies for battery chargers were reviewed in [17–20]. The application of a lithium-ion battery on EV and related technologies were reviewed in [21]. The marketing and consumer aspects regarding EVs and ECSs were reviewed in [22–24]. However, none of the above review papers has focused on the design of system configurations for ECS and their significance. As a result, this paper aims to cover this part and provide an overview on the system planning of ECSs that focuses on various system configuration and design considerations as well as key technologies required for distinct system design.

To provide a sufficient literature survey and cover enough technical contents, this paper covers 143 ECS-related research papers found in open literature. The reviewed papers are categorized according to the ECS system structure discussed in each paper: ECSs without ESSs/REs (18 papers), ECSs with ESSs without REs (23 papers), ECSs with REs without ESSs (19 papers), and ECSs with ESSs and REs (59 papers), as shown in Figure 2. As can be seen from the distribution trend, an ECS with ESSs and RE is the most robust and efficient system design since it combines the advantages of both ESS and RE technologies and provides advanced energy management and control mechanisms for various EV charging operations. Figure 3 shows the reviewed papers categorized according to the main technology focuses discussed in each paper, including (1) system design and configuration assessment, (2) system modeling, (3) power and energy control, (4) system cost and profit analysis, and (5) other ECS-related aspects. Figure 4 shows the reviewed papers categorized according to the years of publication. Table 1 presents a list of technically related keywords and reviewed papers.

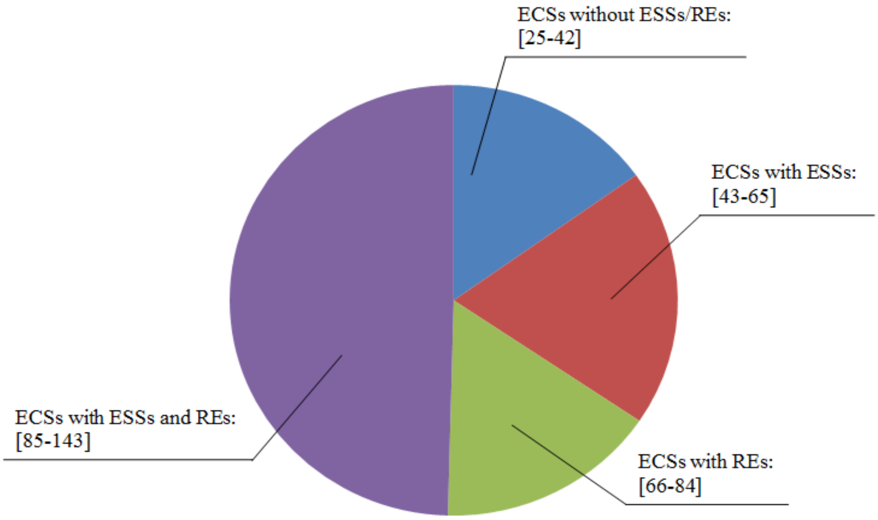

Figure 2. Categories of reviewed papers according to electric vehicle charging stations (ECS) configurations.

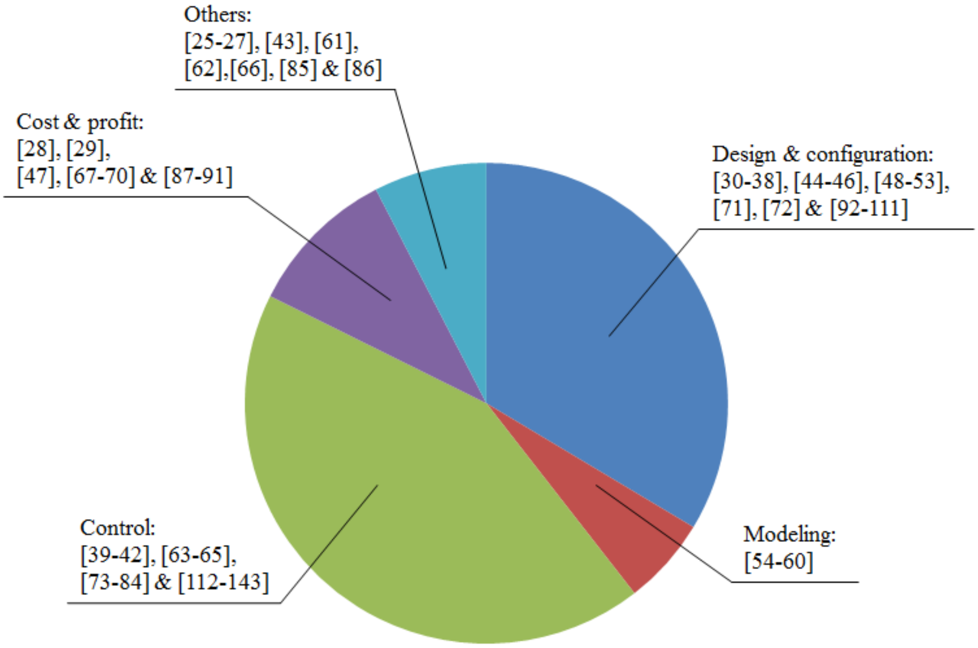

Figure 3. Categories of reviewed papers according to technical focuses.

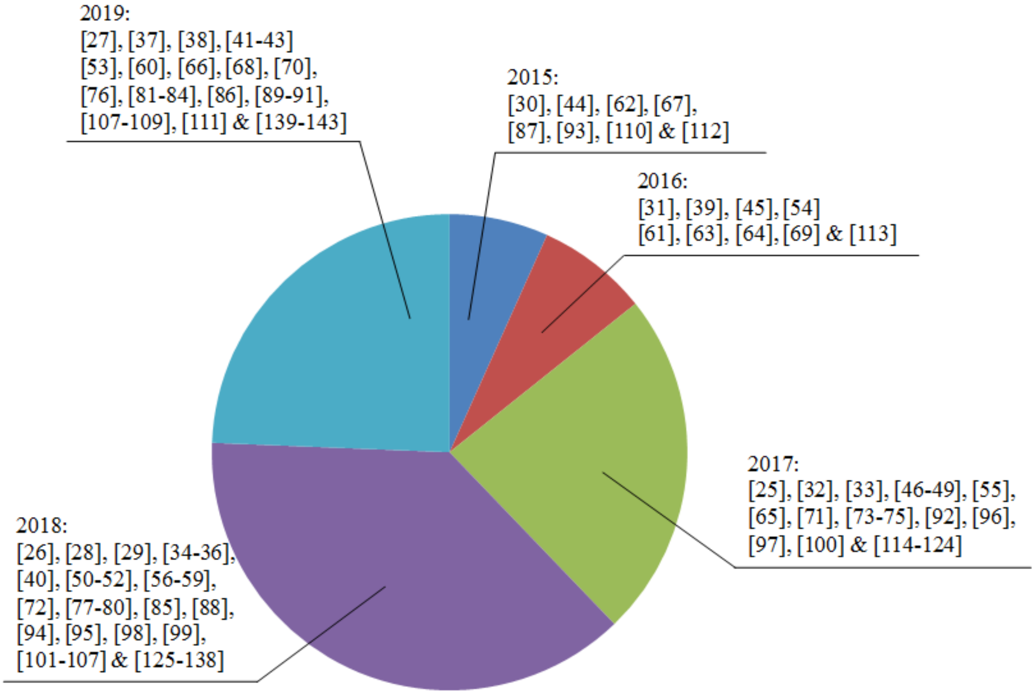

Figure 4. Categories of reviewed papers according to years of publication.

Table 1. List of technically related keywords and reviewed papers.

List of Technically Related Keywords	Reviewed Papers
Electric vehicle (EV), green vehicle, hybrid electric vehicle (HEV), plug-in electric vehicle (PEV), plug-in hybrid electric vehicle (PHEV)	[25–27,29–31,33,34,36,37,42–51,55–60,63,64,67–74,76,77,79,80,82,83,85,86,88–92,94,96–100,102,107–111,113–116,119,121,123,126,128,129,131,132,135,140–143]
Charging infrastructure, charging station, electrical vehicle charging station (ECS), electric vehicle supply equipment (EVSE)	[25,31,34,35,37,40,41,43,45,55,67,68,71–75,80,87,88,90,91,93–96,100–102,104–106,112,115,117–119,121,124–131,134,138–140]
Fast charging, fast charging station (FCS), high rate charging	[27,44,45,47–49,57–59,64,82,89,107,109,110,113,114,116,123,126,136,137]
Battery charging station, battery swapping station, exchangeable batteries	[34,42,55,56,71,81]
Allocation, capacity, configuration, design, installation, placement, planning, sizing and siting	[30,31,33,35,36,56,86,88,92,96,98,101,104]
Constant price, dynamic price, menu-based pricing, pricing, tariff	[28–30,39,41,63,67,68,91,130–132]
Cost, cost–benefit analysis, day-ahead price, economic feasibility, electricity price, energy trading, market price, profit maximization, real-time price, wholesale electric energy price	[37,45,47,63,69,70,74,87,89,94,99,128,129]
Battery degradation, battery energy storage, distributed storage, energy storage, flywheel, hybrid energy storage, lead acid battery, second life battery, second-use battery, split battery energy storage, superconducting magnetic energy storage, vanadium redox flow battery	[43–51,55,57–59,62–64,72,77,81,86,88,89,92,93,97,100,101,103,104,107,108,114–117,119,121,123,128,129,131,133,134,136,140–142]
Active distribution network (ADN), grid, power distribution network, power distribution system, power system flexibility	[25,27,58–60,75,76,86,101,110,117,118,125,128,136]
Smart grid	[29,34,36,69,72,85,100,119,121,134,135]
AC/DC conversion, cascaded H-bridge converter, DC–DC converter, inverter, multiport converter, neutral point clamped converter, power electronic transformer, there-level DC–DC converter	[44,113–115,123,134,135,143]
Nested logit model, optimal allocation model, pricing model, spatial and temporal model, statistic EV behavior model, uncertainty modeling	[31,33,35,40,83,91,97]
Algorithm-distributed optimization, Benders decomposition, bi-level programming, Bayesian game, constraint-generation, distributionally robust optimization (DRO), game theory, generalized Benders decomposition, genetic algorithms, Lyapunov optimization, mixed integer linear programming, Monte Carlo, multi-objective optimization, multi objective whale optimization algorithm (MOWOA), oligopoly, particle swarm optimization (PSO), queuing theory, randomized algorithm, shared nearest neighbor (SNN) clustering algorithm, stochastic dynamic programming (SDP), stochastic programming, Voronoi diagram, wait-and-see solution (WS)	[29,31,33–37,39–42,46,51,55–57,67,68,70,74–76,80,81,83,88,90,97,100,102,107,109,112,115,117,118,124–126,131–133,137–142]
Admission control, charging control, charging current control, coordinated control, direct load control, distributed control, droop control, energy management, frequency regulation, fuzzy controller, PID controller, power control, predictive control, voltage balance control (VBC), voltage control, voltage loop control	[28–30,36,40–44,48,64,70,73,76,77,79–82,85,90,93,105,106,108,113–115,118,119,121,123–125,127,128,131,132,135–138,140,141]
Clean energy, green energy, renewable energy, renewable power, solar PV, wind	[67–69,71,72,74,85,86,88–90,92,93,95–98,101–109,111,112] [117–119,124,125,127,130–134,139–143]
Behavior, charging behavior, consumer behavior, frequency response, performance evaluation, user satisfaction degree	[26,28,30,33,35,40,43,63,86,87,126,128,136]

2. ECSs without REs and ESSs

If an ECS is directly connected to a grid without other energy support such as RE and ESSs, as shown in Figure 5, the charging power is completely supplied by the grid. As a result, the grid receives full impact from the irregular charging/discharging loads of EVs, thus increasing the level of power quality (PQ) problems in the power distribution system. In [25–42], ECSs not using RE and ESSs were investigated. Based on the results presented in the reviewed papers, in some cases, only limited EVs can possibly be connected. It seems that the simplicity in system design and low cost constitute its advantages. S. Deb et al. [25] tested and quantified the impact of ECSs on the IEEE 33 bus system (a standard radial network); the maximum load cap must be adjusted to match the required voltage robustness of each bus. F. Sánchez et al. [26] pointed out that EVs could help power grids in improving frequency response through fast discharging control. The authors also predicted the impact of daily charging loads in three types of large-scale ECSs on a grid's frequency stability. Simulation results showed an improvement in frequency stability and control responses with the proposed control scheme. Issues concerning dynamic state observation problems caused by measurement delay and the superiority of bidirectional charging over unidirectional charging were discussed. The impact of fast EV charging stations on the PQ of distribution systems in medium-size Latin America cities was studied by L. G. González et al. [27]. The simulation and analysis of a 50 kW ECS showed that an ECS caused only minimal harmonic distortion in a power distribution system. In [28], the charging methods of four EVs in Shanghai, China were simulated, and the commercial potential of a smart ECS was also evaluated. In order to maximize the profit, a joint admission and pricing algorithm was proposed in [29] to optimize the profit of ECSs, where pricing, control, and scheduling were all optimized based on a tandem queuing network model. A more than 500% higher profit was observed using the proposed method compared to a common benchmark method. The design and configuration of ECSs were explored in [30–38]. I. S. Bayram et al. [30] proposed two frameworks for the capacity planning of ECS networks with various charging technologies to satisfy multiclass customers with various charging needs. The two frameworks were targeting at large and small networks and could both enhance grid stability and provide a good quality of services. In [31], the placement of fast charging stations (FCSs) on a round freeway was planned using a shared nearest neighbor (SNN) clustering algorithm. Incentive-based demand response programs (DRPs) were used in [32] to build a model to optimize the placement and capacity of ECSs that considered various costs. A swarm optimization algorithm was then used to solve the problem. C. Luo et al. [33] optimized the placement of ECSs in San Pedro District of Los Angeles, CA, USA, using their developed software, the EV Virtual City 1.0, to create balanced benefits among related entities. In [34], stochastic models and the Monte Carlo method were used to simulate the behaviors of taxi and bus fleets in order to optimize the capacities of ECSs. Invertor and user's benefits were coordinated in [35] using a bi-level optimal allocation model which could be simplified into a single-layer optimization model with Karush–Kuhn–Tucker optimality conditions. S. Wang et al. [36] modeled three types of ECSs and used a multi-objective evolutionary algorithm to optimize the planning of an ECS infrastructure. In [37], a multi-objective framework was proposed for the placement planning of an ECS infrastructure for Guwahati, India, considering economic factors, grid characteristics, and EV usage. Then, Pareto dominance, chicken swarm optimization (CSO), and teaching–learning-based optimization (TLBO) were used to solve the planning problem. An ECS planning model with minimized losses and a maximized EV flow was proposed in [38]. A multi-objective grey wolf optimizer (MOGWO) algorithm and fuzzy satisfaction-based decision-making method were used to obtain the final result, which was tested on the IEEE 123-bus distribution system connected to a transportation network. Control strategies were studied in [39–42]. P. You [39] proposed a cooperative charging strategy based on dual decomposition and Benders decomposition to allow EVs to share energy with each other, which is similar to using EVs as ESSs. In [40], randomized algorithms were used for ECS energy management with a day-ahead upper limit of power consumption. The charging schedule was optimized in [41] by incorporating fast and regular charging modes into one ECS. X. Tan et al. [42] used a generalized

Benders decomposition algorithm to optimize the charging schedule of an ECS with a battery swapping service. Based on the discussions given in the above reviewed papers, it can be concluded that this system configuration is only applicable when the charging loads are always predictable and relatively small, and the grid must thus be able to supply the charging loads with its control capability and retain an acceptable stability and power quality grades.

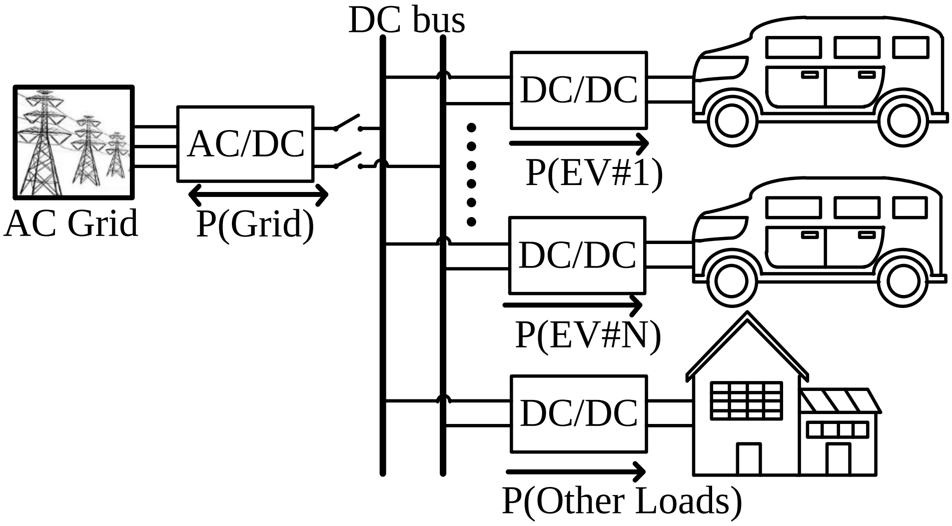

Figure 5. Typical system configuration of a grid-connected ECS without renewable energy (RE)-based power generation and energy storage systems (ESSs).

3. ECSs with ESSs

The system configuration of ECSs embedded with ESSs is shown in Figure 6. In this system design, a number of optimal energy control and management algorithms can be performed. Popular technical topics discussed in this category include quantitative analysis in various system designs, system configuration planning, modeling, control, and hybrid ESS (HESS) design for applications in ECSs [43]. In [44–53], the design and configuration of ECSs were discussed. M. Vasiladiotis and A. Rufer [44] proposed a modular multiport power electronic transformer based on a delta-connected cascaded H-bridge converter to incorporate a split-battery ESS for ultrafast EV charging service. In [45], the capacity of an ESS in a fast charging station (FCS) was optimized by considering charging demand, energy loss, and life cycle. In [46], a stochastic method used to optimize the number of ESSs in an urban ECS supported by second-life EV batteries was developed. M. Gjelaj et al. [47] proposed a method for minimizing system operating costs in which installation costs, connection costs, and ESS life cycle costs were considered to reduce DC ECS operating costs. Then, the authors further designed a new bidirectional DC ECS that integrated a properly designed ESS, and IEC 15118 was adopted as the interface to achieve fast charging in low voltage (LV) grid [48]. Later, the optimal capacity of an ESS on a given set of design conditions was studied in [49]. The design of a wireless flywheel EES for a fast charging station (WFFCS) was proposed by A. H. Fahad and H. A. Gabbar in [50]. V. Salapić et al. [51] proposed a mixed integer linear programming (MILP) scheme for the optimal capacity and control of an ESS. In [52], a new FCS with modular lithium-ion batteries was designed for an existing low-voltage grid with a reduced cost and charging time. The application and stochastic modeling-based capacity planning of batteries in FCSs was explored in [53] to optimize charging service. Modeling techniques played an important role in [54–60]. T. Martinsen [54] proposed a model of an ECS with a stationary lithium-ion battery pack in which ESS cost and degradation issues were considered. An optimized model including an ECS, a battery-swap station (BSS) and an ESS was proposed by Y. Wang et al. [55]. In [56], a novel mixed queuing network (MQN) model was proposed to evaluate the performance of ESSs, a model which took parameters that affect battery swapping and charging station (BSCS) capacity into account. A Markov chain was used in [57] to determine the state space of an ECS to establish a random ECS load model, and queuing theory was used to analyze and optimize costs and profits. L. Richard and M. Petit [59] proposed a mathematical model describing a grid-connected ECS with ESS degradation, and they discussed the tradeoffs between ESS capacity and ECS rated power. A 250 kWh ESS successfully reduced an ECS power rating to 2/5 in the case of three 120 kW ECS units. They also proposed an ECS model to study utility power price and battery degradation under different conditions in [59]. In [60], M. Pertl et al. proposed a mathematical model using simple equivalent time-variant aggregation storage with predictive function suitable for different market/flexible loads. HESSs with different architectures were proposed in [61,62], where J. Deng et al. [61] proposed a control strategy that could extend the life of an HESS, and T. D. Atmaja and Amin [62] applied an HESS to a mobile charging station (MCS). The control of an ECS in this category was discussed in [63–65]. Historical data and the predicted trend of electricity price were used to design a real-time power and energy control scheme for an ECS based on a heuristic approach combined with deterministic methods [63]. B. Sun et al. [64] proposed a control algorithm to eliminate the need for any digital communication between power converter interfaces to make flywheel ESSs provide power in FCSs. In [65], the supply and demand of a large number of ECSs was optimized using a proposed framework based on day-ahead electricity market. Overall, the control and application of ECSs with ESSs have been relatively less studied because of the more recent trend of using the batteries of connected to EVs as required ESSs, which immensely lowers the cost while benefitting from similar results to employing extra ESSs. Based on the discussions given in the above reviewed papers, it has been found that ESS's charge/discharge functions are normally utilized to expand the feasible system capacity of ECSs, reduce possible load peaks in connected power grids (peak load shaving), and smooth fluctuations during load changes when necessary.

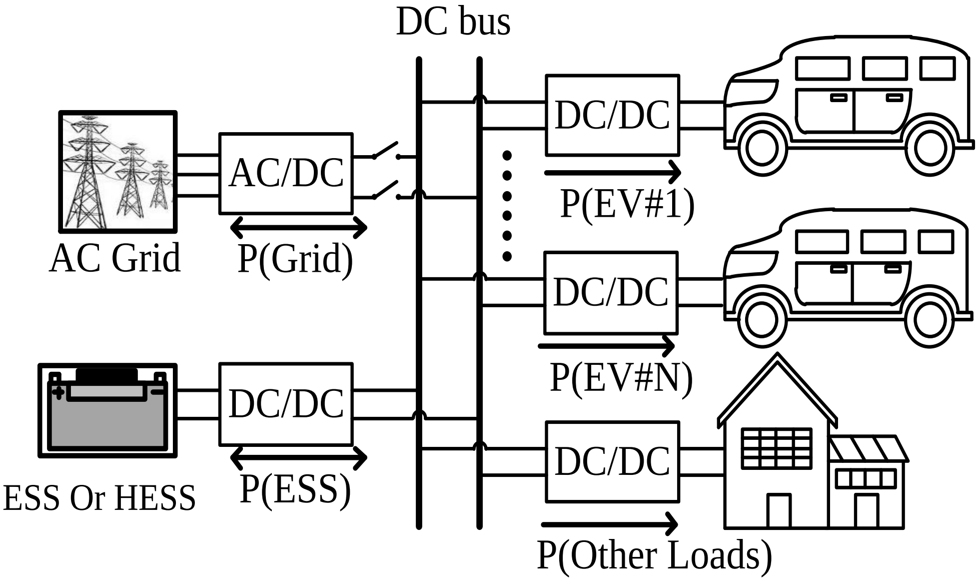

Figure 6. Typical system configuration of a grid-connected ECS with an ESS.

4. ECSs with REs

As shown in Figure 7, ECSs with RE-based power generation can reduce the peak load demand on a power grid to a certain extent. In such a system design, the EVs can even be used as ESSs to assist the regulation of RE-based power generation, which is naturally unpredictable, if operation priority is given to support the real power of a grid. A. Shukla et al. [66] studied the impact of an FCS on a grid with wind power generation using a model based on a Weibull distribution function. In [67], game theory was used to study the price competition of two ECSs: (1) ECSs with RE-based generation and (2) ECSs supplied solely by a grid. The authors later discussed the price competition again in [68] using a multiplicatively-weighted Voronoi diagram and a Stackelberg game, where ECSs with both large and small capacities were discussed. In both studies, ECSs with RE-based generation yielded better results. W. Tushar et al. [69] minimized the cost of a PV-ECS by classifying EVs into three categories: premium, conservative, and green, depending on if the users are environmentally friendly enough to allow ECSs to use their batteries as extra energy storage devices. In order to develop a more reasonable time-of-use price (TOUP), T. Rui et al. [70] proposed a distributed, PV-based ECS charging model with the best internal price and a distributed algorithm based on Stackelberg game theory for estimating the day-ahead price (DAP). A real-time price (RTP) method was proposed to address operational issues caused by the energy gap between expected PV generation and expected charging demands. T. Sakagami et al. [71] studied the control features of three PV panels with different specifications and EV applications in which an exchangeable battery system (EBS) was assumed. The results showed that the system could supply up to 82.2% of an EV power demand on a sunny day. In [72], a two-stage optimization framework was developed to calculate the optimal capacity and power dispatch of a pair of wind and PV generations in an RE-based ECS system, in which an EV demand model was built using real EV data. In [73–84], the focuses were the control of ECSs with RE-based generation. A solid-state transformer was used in [73] for the energy management of PV-ECSs using a rule-based decision-making method, an energy-bound calculation (EBC) model, and a charging power allocation algorithm. Q. Chen et al. [74] proposed to regulate the charging service of a PV-ECS with an automatic demand response strategy and a dynamic linear model of real-time electricity price. In [75], a convexified model of ECSs was proposed to optimize the charging schedule in terms of charging cost and energy cost, and then charging scheduling was optimized online in [76] using distributed model predictive control while taking multiple ECSs and power/voltage constraints into consideration. In [77], instead of using ESSs, a special application of integrating EV and a power grid was adopted to deal with the influences of power fluctuations and power peaks on a standalone micro grid(MG), in which a voltage controller was proposed based on active power/voltage (P/V) droop algorithms. The grid voltage was successfully adjusted by charging and discharging the EVs, and the power supply of each EV was separately allocated. K. Dhingra and M. Singh [78] studied the use of ECSs to stabilize the frequency fluctuations in a standalone MG and investigated the frequency stability of an MG with a virtual synchronous generator (VSG) using the Matlab/Simulink software environment. A coordinated sectional droop charging control (CSDCC) strategy was proposed in [79], and EVs were used to adjust the frequency of an RE-embedded power grid; results showed that the more EVs connected to the grid, the better the adjustment performance. In [80], a tri-level theoretical approach was proposed to perform the separate energy management of EVs and ECSs, where system operation constraints were in the highest level, ECS profit was in the second level, and EV charging cost was in the lowest level. A real-time power control algorithm was proposed that was based on a queuing theory–Lyapunov optimization framework to maximize the system utilization rate in a smart community MG (SCMG), where RE-based power generation was used for the charging of the EV and simultaneously providing power to households [81]. W. Khan et al. [82] proposed a low harmonic ECS model and a power flow control strategy for a PV-based ECS to reduce the demand of real power from the grid and thus reduce the overall real power losses. In [83], the load management capabilities of a PV-based ECS were evaluated based on three time-frame charging, i.e., morning, afternoon and night charging. The results obtained from the three EV charging sequences were compared with different means: heuristic, optimization, and stochastic programming. Z. Akhtar et al. [84] compared point-of-load and mid-feeder compensation methods for over-voltage and under-voltage in low-voltage grids with a high penetration of PV generation and ECSs. Both methods had their own strengths and drawbacks. Based on the technologies and control problems investigated in the above reviewed papers, it is obvious that major technical issues in this category include the optimal system design of RE and advanced control strategies for solving the problems of inevitable power fluctuations and voltage stability caused by REBPG on various system configurations.

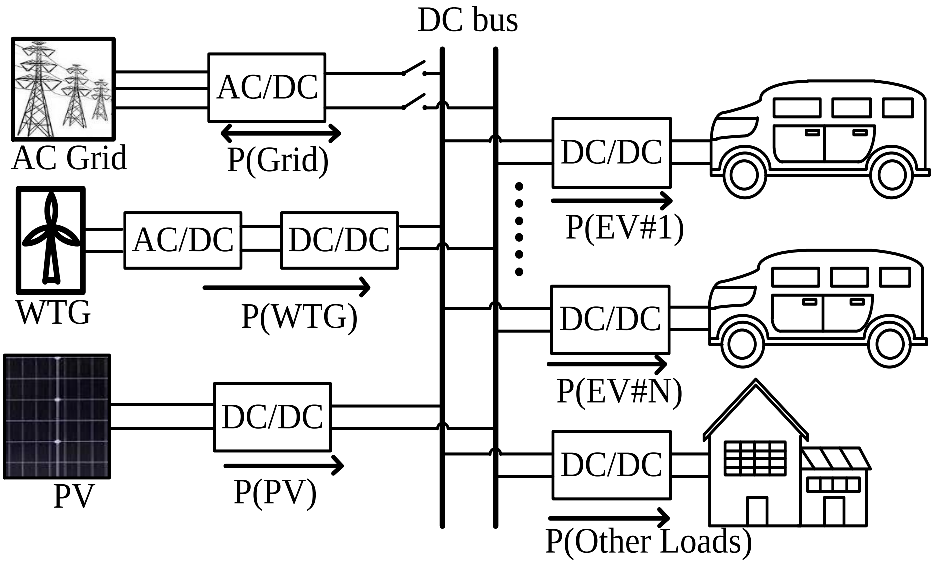

Figure 7. Typical system configuration of a grid-connected ECS with RE-based power generation.

5. ECSs with ESSs and REs

As shown in Figure 8, the integration of RE-based power generation, various ESSs and grid-tied ECS systems constitutes a powerful system with a number of technical merits. RE-based power generation can be used to assist or take charge in EV charging and peak power flow-shaving, and the related power losses of the connected power grid can be reduced; moreover, a better PQ can be achieved. The inevitable power fluctuations of RE-based power generation units can be improved to some extent or even completely eliminated with the addition of ESSs. K. Mahmud et al. [85] discussed technical approaches related to EVs and ECSs, including impacts of ECSs on the grid, the applications of RE-based power systems in ECSs, power control methods in the Internet of Energy (IoE), EV integration, and security concerns. In [86], a new multi-stage distributed expansion planning model was proposed to consider investments in distribution network assets, RE-based power generation, ESSs, and ECSs. The variability of RE-based power generation was generated using a *k*-means clustering technique. P. Sarikprueck et al. [87] proposed a hybrid method to forecast short-term market price using three different data clustering techniques. The Electric Reliability Commission of Texas wholesale market price was used to validate the proposed hybrid method. The total annual cost of energy (ACOE) of ECS, ESS and RE systems was optimized in [88]. The charging power of EVs and the RE-based power required to operate an ECS were generated using Markov chain Monte Carlo (MCMC) method, and the overall system power allocation was obtained using a genetic algorithm (GA) and deterministic optimization tools. L. Yang and H. Ribberink [89] studied a DC ECS model and calculated the cost of electrical energy and an ESS to assess the performance of installing PV-ECSs at a highway service. S. Li et al. [90] used a penalty function-based particle swarm optimization algorithm (PSO) to solve the PV-ECS optimization problem with a set of objective functions. The objective functions included charging cost and charge–discharge cycle limit of an ESS subject to a given set of output constraints. In order to avoid residential power demand peak overlapping with an ECS power demand peak, a coordinated model was proposed and solved using a heuristic solution in [91] for the dynamic pricing of ECS services to encourage EV users to shift their charging periods to less expensive hours. Based on the discussions presented in the above reviewed papers, it can be expected that with proper communication and control algorithms, some optimization objectives in operating ECSs with ESSs and RE can be readily achieved. Thus, this system design has strong potential to become the mainstream of future ECSs. Potential topics and technical issues in this system design category include statistical algorithms for sizing ESSs, optimal system design, and coordinated control strategies for various system configurations. The mathematical modeling and simulation of ECSs is an important tool for various investigations carried out in this category.

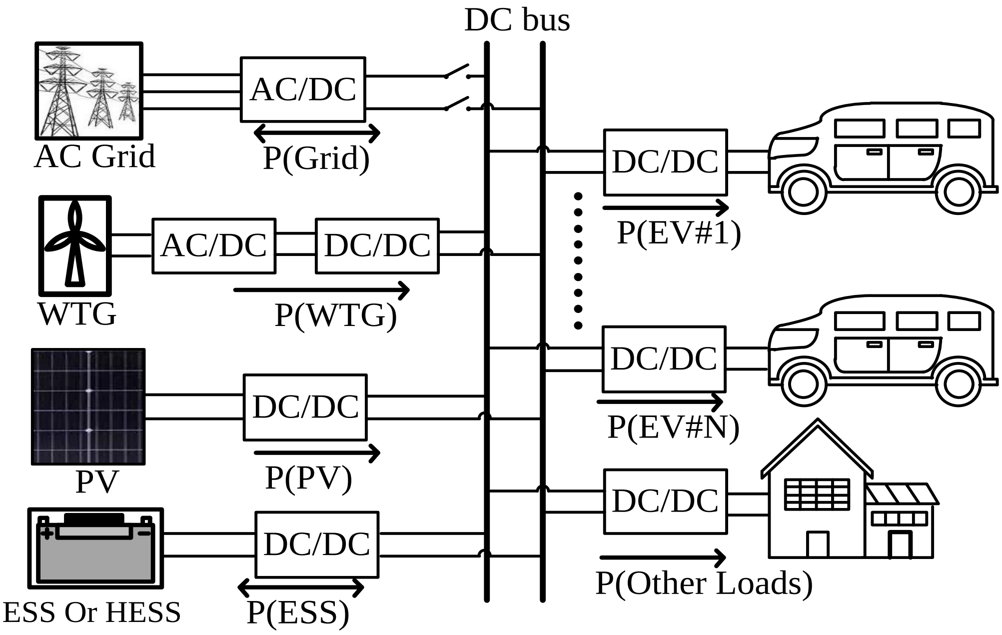

Figure 8. Typical system configuration of a grid-connected ECS with ESS and RE power generation.

In addition to the above reviewed papers regarding the impact, cost, and profit of ECSs, papers investigated key technologies in various ECS systems, energy management sizing and control issues in practical applications are reviewed in the rest of this subsection. The capacity and configuration design of ECSs were explored in [92–111]. A Erlang-loss system and stochastic programming were used to model uncertainties including EV, PV-based power generation and electricity prices in [92], in which attribute sets and a clustering-based scenario generation method were used to generate the scenarios for the investigation. In [93], flywheel, supercapacitor, and superconducting magnetic energy storage (SMES) were compared to explain that SMES had the best performance in terms of maintaining the DC bus voltage of a grid-connected PV-ECS; a Matlab/Simulink simulation was presented to verify the proposal. S. H. Baik et al. [94] explored the optimal capacity of ECSs for maximum profit. In order to reduce the operation and energy costs of a hybrid power generation embedded ECS, M. Nizam and F. X. R. Wicaksono [95] determined the best ESS design from three types of ESSs. In their study case, a PV-lithium ferro phosphate (LFP) battery was chosen as the best solution. In [96], the authors explored the vertical installation of PV-based power generation for ECS application. J. Ugirumurera and Z. J. Haas [97] designed a search-based algorithm to determine the optimal number of PV panels and ESS capacity in a fully RE-powered ECS, where the PV generation discontinuity was modeled using a 3D Markov chain model. The application of PV-based power generation in ECSs was studied in [98]. In [99], the hybrid optimization of multiple energy renewables (HOMER) software was used to analyze CO_2 reduction and possible cost savings in an ECS design example in Bangladesh, in which PV and biogas were investigated. The Monte Carlo method and a genetic algorithm (GA) were used to find the best ECS designs in [100]. In [101], a second order conic programming problem was formulated and used to find a comprehensive optimization ECS model. In [102], a comprehensive two-stage approach was proposed to select the location and capacity of a fully RE-powered ECS where the uncertainties were described using a family of inexact distributions around an empirical distribution mathematical model, and the distances were described using the Kullback–Leibler divergence algorithm. A particle swarm optimization (PSO) algorithm was used in [103] to propose modeling and optimal capacity calculation procedures for distributed generation (DG), HESS, and ECS loads. X. Han et al. [104] used teaching–learning-based optimization (TLBO) and PSO algorithms to find the best ECS configuration.

B. Singh et al. [105,106] proposed an uninterrupted power supply system for ECS applications. In the studied case, a PV-based power generation, an ESS, a two-winding single-phase induction motor coupled diesel generator, and a single-phase two-leg voltage source converter (VSC) were integrated to achieve two objectives, i.e., reducing costs and maintaining a good PQ. In [107], a mathematical model of a PV-ESS-ECS was used in solving optimization problems for the planning of ECSs, i.e., the minimization of the grid connection cost of ECSs in some regions subjected to a given set of preset operational conditions of power grids. A. Esfandyari et al. [108] discussed the design procedure for a campus PV-ECS grid connection and operation, a study in which ESSs, PV power generation, and models describing local power consumption were taken into consideration. J. A. Domínguez-Navarro et al. [109] used the Monte Carlo method and a genetic algorithm (GA) to find the best ECS designs. A neutral point clamped converter was proposed in [110] to reduce voltage-buck requirement and maintain the voltage balance for an ECS with wind and solar powers, a battery, and a fuel cell. In [111], an isolated multi-port converter was proposed to interface grid, ECSs, RE-based generation, and ESSs through multi-directional power flow control.

The control issues of ECSs were explored in [112–143]. Y. T. Liao et al. [112] used a stochastic dynamic programming algorithm to find the optimal power dispatch of a model with a grid, an ECS, PV generation, an ESS, and a fuel cell connected with a DC bus. In [113], an effective voltage balance control strategy was proposed, one which can be integrated with optional PV panels and a battery by using a three-level DC/DC converter that also improves the quality of the grid current. Later, the authors proposed to use an ESS and a neutral-point-clamped converter to balance split-DC bus voltage [114]. A. Hassoune et al. [115] proposed an intelligent topology to control the power flows in an ECS system through an optimization algorithm aimed to stabilize the energy flow of systems. An optimization algorithm was used in [116] to build a demand-side power flow management strategy, and ESS capacity design methods were explored while considering ECS charging statuses. With the proposed algorithm, charging requirements can be controlled within the reference maximum. K. Kasturi and M. R. Nayak [117] used a control technique to balance power flow and used a multi-target Whale Optimization Algorithm (MOWOA) to find the optimal configuration of an ECS with a PV-ESS subject to a minimized cost. In. [118], several ECS intelligent operation modes were proposed, and a power flow smoothing control scheme was established to demonstrate the power flow control results in a Matlab/Simulink environment. Three different charging modes (quick, green, and budget) were designed in [119] to control charging current, thus allowing users to select a charging mode according to their needs. For investigating G2V/V2G charging modes in a PV-ECS, A. T. Radu et al. [120] built a mathematical model using CPLEX and optimized the operation with battery ESSs. In [121], an intelligent management system for coordinating an ESS, a DG, and an EV was achieved; in this system, the EV charging demand and the data for the energy consumption curve were directly obtained from an EV on-board diagnostic (OBD) system. The effectiveness of the proposed method was confirmed with one month of observation. In [122], CPLEX software was used to propose a mixed-integer linear programming (MILP) optimization model to study the effects of varying loads of aggregated ECSs on an island MG and to find the optimal scheduling of ESSs. L. Tan et al. [123] proposed a high-power three-level DC-DC converter to achieve DC power balance in FCSs. Active and passive DC power balance management techniques were used to balance the power and eliminate current fluctuations, respectively. J. Zhang et al. [124,125] proposed a consensus network control system based on game theory to limit ESS charging within a certain state of charge (SOC). The same authors further proposed a multiple PV-ECSs, hierarchical-distributed, energy management algorithm to obtain a cooperative and generalized solution that took the stabilized battery average available capacity (AAC) and the maximized charging power into account. In order to minimize operating costs, a method to set bounds for optimal control was proposed in [126] that was based on wind power, solar power, and electricity prices, all of which were modeled using support vector regression and a martingale model forecast evolution and then solved using a wait-and-see solution. Y. Wu et al., K. Chaudhari et al., and S. Agrawal et al. [127–129] proposed an electricity price-based real-time optimization algorithm on various power management strategies, certainty and regularity-based hybrid optimization algorithms, and decided heuristic hybrid algorithms, respectively. In [130], power flows were optimally coordinated based on a given set of capacity limits and EV service time periods, and an EV charging online pricing mechanism was proposed to provide users with different charging services with their respective prices and time consumptions. The objective of the proposed optimal control algorithm is to maximize social welfare and ECS profits. A stochastic dynamic programming (SDP) algorithm was used in [131] to investigate a multi-functional EV charging service optimization framework and propose a new method for evaluating ECS impacts on grids. A rule-based energy management scheme (REMS) was proposed in [132] to provide an uninterrupted daytime charging and constant price. A charging/discharging control scheme using a Markov decision-based optimization algorithm was proposed for a hybrid energy storage system (HESS) based on a lead acid battery (LAB)–vanadium redox flow battery (VRB) [133]. L. Novoa and J. Brouwer [134] investigated four different intelligent control algorithms for power converters with the aim of achieving the optimal power scheduling of an ESS and a PV-based micro-grid. The optimal duty cycle control of DC/DC power converters was studied in [135] to improve the regulation performance of DC bus voltage and the regulation efficiency (up to 99%), as well as to decrease MG power losses. In [136], a control algorithm for AC/DC and DC/DC converters used in ECSs was proposed to mitigate the adverse impact of ESS-ECSs on the grid. T. Zhou et al. [137] used a hierarchical game approach to optimize the energy and reserve management of a large number of EVs and FCSs in real time. A leader–follower game was used to model the system into a bi-level optimization problem, and a mathematical programming with equilibrium constraints was used to solve the problem. In [138], a control scheme based on a sample average approximation method and a two-stage stochastic programming method were proposed to simulate a system model containing commercial buildings, ECSs, and a power grid. Later, a hybrid algorithm of a sample average approximation and an enhanced progressive hedging algorithm (PHA) with constrained generation algorithm frameworks was proposed to solve a previously proposed two-stage stochastic programming model [139]. This model considered long-term and short-term decisions, with the designed ECS integrating RE-based power generation. In [140], a four-stage intelligent optimization control algorithm was proposed for a bidirectional PV-ECS system in which the power supply and demand among EVs, ESSs, grids, and deferrable loads can be simultaneously balanced. In [141], a two-stage admission and scheduling mechanism was proposed. This was done by studying solar irradiance prediction errors and proposing an ECS figure of merit. P. García-Triviño et al. [142] proposed a decentralized control method (DCM) for a medium-voltage (MV) ECS. The proposed method utilized fuzzy logic algorithms to control the ESS and the grid, with the goal of maintaining the voltage and battery SOC within appropriate ranges as well as balancing the power of each device at all times. The proposed control method was validated by a Monte Carlo simulation of two hundred cases (on different daily irradiances, an initial ESS SOC, and the number of EVs charged). A modified Z-source inverter (ZSI), which is very suitable for grid-connected DG applications, was proposed in [143] to interface EV charger, ESS, DG, and the grid for applications in parking lots, shopping mall, etc. The proposed inverter can be used in string inverters for residential applications as well.

6. Conclusions and Discussion

This paper has reviewed a total of 143 EV- and ECS-related technical research papers including nine papers for background and general information, 17 subject-oriented review papers, and 117 research papers previously published in open literature. Reviewed ECS-related papers were categorized into four types according to the investigated system configurations: (1) grid-tied ECSs without RE-based power generation and ESSs; (2) grid-tied ECSs with only ESSs; (3) grid-tied ECSs with RE-based power generation; and (4) grid-tied ECSs with both RE-based power generation and ESSs. The main technical focuses reviewed included the following: (1) the system planning and design of configurations; (2) system modeling for various studies; (3) energy management and control algorithms; and (4) system optimization methods that take cost and profit into account. Based on the papers reviewed in each category, it has been found that the fourth type of system design, grid-tied ECSs with both RE-based power generation and ESSs, is the most popular and advantageous. In fact, it has been expected to have the most future potential in the ECS industry and related applications. With the integration of RE-based power generation, various types of ESSs or HESSs, and with the-state-of-art communication, optimization and control algorithms, a multifunctional ECS can be achieved. In addition to EV charging, other potential functions include the real-time active power support for power grids, the power smoothing control of RE-based power generation, real-time optimal energy efficiency control, the peak shaving and load shifting control of power grids, and other power quality control capabilities, e.g., voltage and frequency stability improvements. However, tradeoffs must be made between the aforementioned optimization goals, unavoidable costs, and possible impacts on system security and reliability. In this respect, some innovative system operating concepts and technical issues in ECSs are urgently needed for researches, e.g., the application potential profit of using new power switching devices based on wide-bandgap (WBG) materials such as silicon carbide (SiC) and gallium nitride (GaN), as well as advanced control techniques for designing multifunctional ECS's power converter systems. The investigation on the significance of the flexibility that portable ESSs provide in ECS networks is also a potential research theme in ECS fields. As shown in Figure 9, the potential applications of portable ESSs in grid-tied ECSs especially integrated with variable RE-based power generation are numerous and could cover a full technical spectrum ranging from grid-support control functions in ECSs embedded with larger-scale RE-based power generation, smart grid-related power, and energy systems to those primarily related to the energy optimization objectives in active power distribution networks, industrial sectors, and even into the domain of the state-of-the-art smart home technologies.

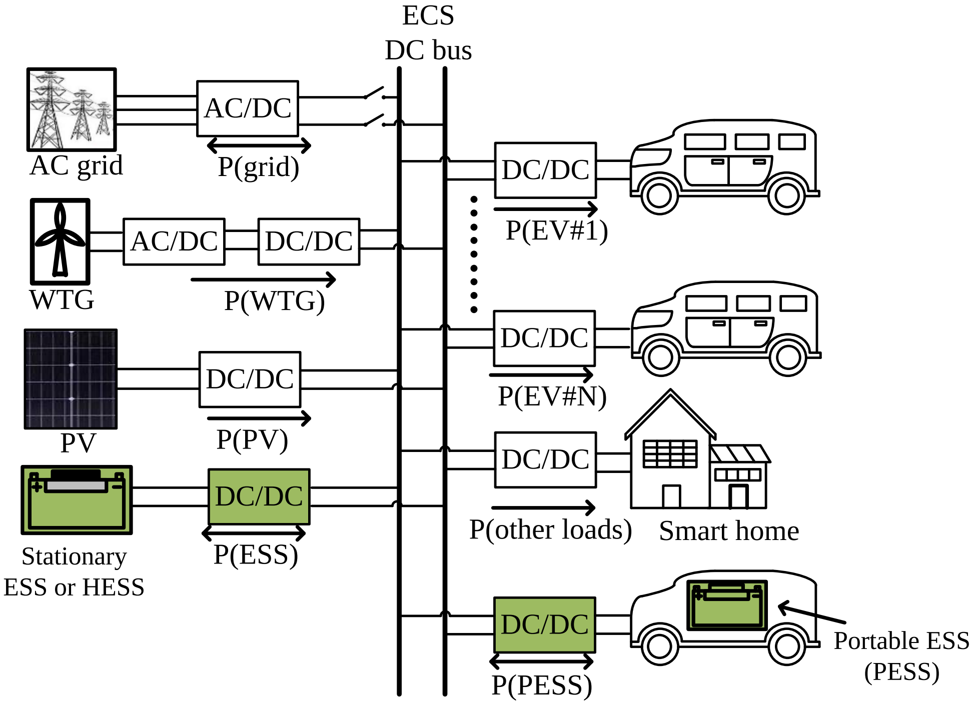

Figure 9. The system configuration of a grid-connected ECS with RE power generation, a stationary ESS and a portable ESS.

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