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Review

A Review of Capacity Allocation and Control Strategies for Electric Vehicle Charging Stations with Integrated Photovoltaic and Energy Storage Systems

Ming Yao, Danning Da *, Xinchun Lu and Yuhang Wang

School of Automobile and Traffic Engineering, Jiangsu University, Zhenjiang 212000, China; ymluck@ujs.edu.cn (M.Y.); 2222304095@stmail.ujs.edu.cn (X.L.); 2222304084@stmail.ujs.edu.cn (Y.W.)
* Correspondence: 2222204145@stmail.ujs.edu.cn

Abstract: Electric vehicles (EVs) play a major role in the energy system because they are clean and environmentally friendly and can use excess electricity from renewable sources. In order to meet the growing charging demand for EVs and overcome its negative impact on the power grid, new EV charging stations integrating photovoltaic (PV) and energy storage systems (ESSs) have emerged. However, the output of solar PV systems and the charging demand of EVs are both characterized by uncertainty and dynamics. These may lead to large power fluctuations in the grid and frequent alternation of peak and valley loads, which are not conducive to the stability of the distribution network. The study of reasonable capacity configuration and control strategy issues is conducive to the efficient use of solar energy, fast charging of EVs, stability of the distribution network, and maximization of the economic benefits of the system. In this paper, the concept, advantages, capacity allocation methods and algorithms, and control strategies of the integrated EV charging station with PV and ESSs are reviewed. On the basis of the above research, the current problems and challenges are analyzed, and corresponding solutions and ideas are proposed.

Keywords: electric vehicle charging station; photovoltaic system; energy storage system; capacity allocation; control strategy

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1. Introduction

In recent years, public concern over environmental pollution, rising oil prices, and reduced use of fossil fuels has prompted the international community to turn its attention to electric vehicles (EVs). Electric vehicles are increasingly respected by consumers as a means of transport due to their low electricity prices and low pollution. Traditional fossil-fuel-based vehicles are being replaced by EVs to reduce fossil fuel consumption and carbon emissions [1]. One potential challenge for the widespread adoption of EVs will be the insufficient charging station infrastructure or, in more developed countries, the limited capacity of existing charging stations [2]. It is not just the high price or limited autonomy that restricts people from buying electric cars, it is the inadequate infrastructure and poor planning of charging stations [3]. Therefore, the construction of charging station infrastructure, along with capacity allocation and control strategies, has garnered significant scholarly interest.

With the development of the global economy and the overuse of conventional fossil energy sources such as coal and oil, the problem of energy shortages and environmental deterioration has become increasingly serious [4]. Therefore, countries all over the world have turned their attention to renewable energy [5]. Solar photovoltaic (PV) technology has been widely promoted in the field of power generation due to its advantages of lower cost and zero greenhouse gas emissions compared to fossil fuel power generation. From the point of view of global installed capacity, solar PV has become the third largest renewable energy source after hydropower and wind power [6]. However, solar PV generation suffers from the disadvantages of poor predictability and unstable power generation due to the effects of uncertain weather and seasonal variations. Therefore, the high penetration of this technology in the distribution network can negatively affect the quality and reliability of electric service. Energy storage systems (ESSs) help to cope with the indirectness and randomness of renewable energy generation [7]. At this time, it is necessary to add ESSs to ensure the uninterrupted operation of the power grid and improve its stability.

Energy storage is an emerging technology that stores electrical energy and delivers it according to the power demand of the load system. It is capable of storing excess power generation and discharging it at peak times to control energy flow. As a result, it plays an important role in electric vehicles, microgrids, and renewable energy systems, gaining favor with investors and industry participants. Different ESSs have different energy storage characteristics. The right ESS can not only provide a longer power supply for EVs and maintain grid stability but also save on the investment cost of charging stations. Therefore, it is profitable to replace traditional coal-fired power generation by combining PV with ESSs to cope with higher future power demand and maintain grid stability.

In response to the rapid development of EVs, charging infrastructure will be widely established, and the construction, planning, and control of charging facilities will become particularly important. Integrated PV and energy storage charging stations, as one of the most promising charging facilities, combine PV systems, ESSs, and EV charging stations. They play a decisive role in improving the convenience of EV charging, saving energy, and reducing polluting emissions. This paper first introduces the concepts related to EV charging stations with integrated PVs and energy storage. Then, it reviews their capacity configuration, system control strategy methodology, and modeling, thus filling the gaps in related research.

1.1. Contribution of this Study

Many experts and scholars believe that in the next few years, the transportation industry will transition to electrification, with EVs gradually replacing fuel vehicles. Therefore, with the vigorous development of EVs, the capacity configuration and system control strategy of charging stations with integrated PV and ESSs have attracted great attention from the academic community. In this paper, we first introduce the integrated PV and energy storage charging station and then review the optimization methods of capacity configuration and the system control strategy of the charging station. This provides researchers with more theoretical and practical support that can be drawn upon.

1.2. Paper Structure

The subsequent sections of this paper are organized as follows: In Section 2, the concepts related to PV power generation systems, ESSs, and charging stations are introduced, which in turn deepens the understanding of EV charging stations with integrated PV and energy storage. In Section 3, the advantages and challenges of integrated PV and storage charging stations are presented. In Section 4, the methods and algorithms for capacity allocation of charging stations with integrated PV and storage are described in detail in terms of both PV and ESSs. In addition, Section 5 presents a study of the system control strategy and the optimization algorithm. Section 6 concludes this paper by summarizing the previous section and pointing out research challenges and future directions.

2. Integrated PV and Energy Storage Charging Stations

2.1. PV Power Generation System

A PV power generation system is a facility that utilizes solar energy to convert light energy into electricity. It is mainly composed of several parts, such as solar PV panels, inverters, racking and mounting structures, and power monitoring systems. Based on the principle of the PV effect, solar radiant energy is converted into DC energy by PV cells, which is then converted into AC power by an inverter and supplied for domestic, commercial, or industrial use. Currently, PV power generation systems are categorized into off-grid and grid-connected systems based on whether or not they are connected to the public power grid [8]. Off-grid systems operate independently and are not dependent on the grid, which is advantageous in remote areas where shared infrastructure is in short supply or where investment costs are too high [9]. Grid-connected systems are connected to the public grid and can either sell excess power to the grid or buy power from the grid. This further improves the efficiency of energy utilization and is suitable for cities or places with a stable power grid. PV power generation systems have the advantages of renewable energy utilization, environmental friendliness, low maintenance costs, and long life. They also reduce the dependence on traditional energy sources, lower energy costs, and produce less carbon emissions for the environment [10]. As technology continues to advance, the use and popularity of PV power systems are increasing. Applications can range from small rooftop installations to large solar power plants, as well as providing clean energy solutions for individual homes, commercial buildings, schools, hospitals, factories, and remote areas. As a result, an increasing number of countries and regions are encouraging and supporting solar power to reduce the dependence on conventional energy sources and combat climate change. PV power generation systems play an important role in sustainable energy development and driving the energy transition [11]. The popularity of EVs will also lead to an increase in PV power systems. A large number of studies have shown that the installation of solar PV panels on the roofs of parking lots not only plays a role in the rational use of resources but also provides a free shade canopy, as shown in Figure 1, which is the structure of a PV parking lot schematic diagram [11]. The installed PV capacity is the sum of the rated power of the solar panels used in a PV power plant. However, it is difficult to determine the magnitude of the output power at different moments in time because the output power of PV modules is strongly influenced by local environmental conditions, such as radiance, temperature, and shadow shading. Among these parameters, temperature has the greatest impact when the temperature exceeds 25 °C [12], and the efficiency decreases by about 0.5% to 0.6% for each degree of temperature increase, depending on the type of solar cell material [13], while a typical PV module converts only 6–20% of the incident solar radiation into electrical energy. The efficiency of PV modules depends on the semiconductor material used to manufacture the solar cells. According to the conductor material, PV panels are classified as monocrystalline silicon solar panels, polycrystalline silicon solar panels, thin-film solar panels, flexible solar panels, and transparent solar panels [14]. According to statistics, nearly 90% of solar cells are made of crystalline silicon wafers. Monocrystalline silicon solar panels have the highest conversion efficiency among the solar panel types, but their panels are more expensive than other solar panels. As for the specific value of installed capacity, this needs to be determined based on the specific PV plant and the solar panels it uses.

Figure 1. Schematic diagram of PV parking lot structure [11].

2.2. Energy Storage Systems

An energy storage system (ESS) is a system that converts electrical energy into other forms of energy and stores it so that it can be converted back into electrical energy when needed [15]. In the field of PV power generation, ESSs play an important role. They can solve the problem of intermittency and volatility in PV power generation and thus provide a stable and reliable power supply [16]. They start storing energy when there is an excess of renewable generation or when electricity prices are low and then discharge it when prices are high or when there is a shortage of renewable generation. They act as a grid load peak as well as increase the utilization of renewable energy sources [17]. ESSs are categorized in a variety of ways, such as according to the form of energy storage, energy storage use, energy storage time, energy storage efficiency, etc. [18]. They can be categorized into mechanical, electrochemical, electrical, thermochemical, chemical, and thermal energy storage according to the form of energy stored, as shown in Figure 2 [19]. Different energy storage technologies contain different energy storage characteristics, such as power rating, discharge time, power density, energy density, service life, etc.

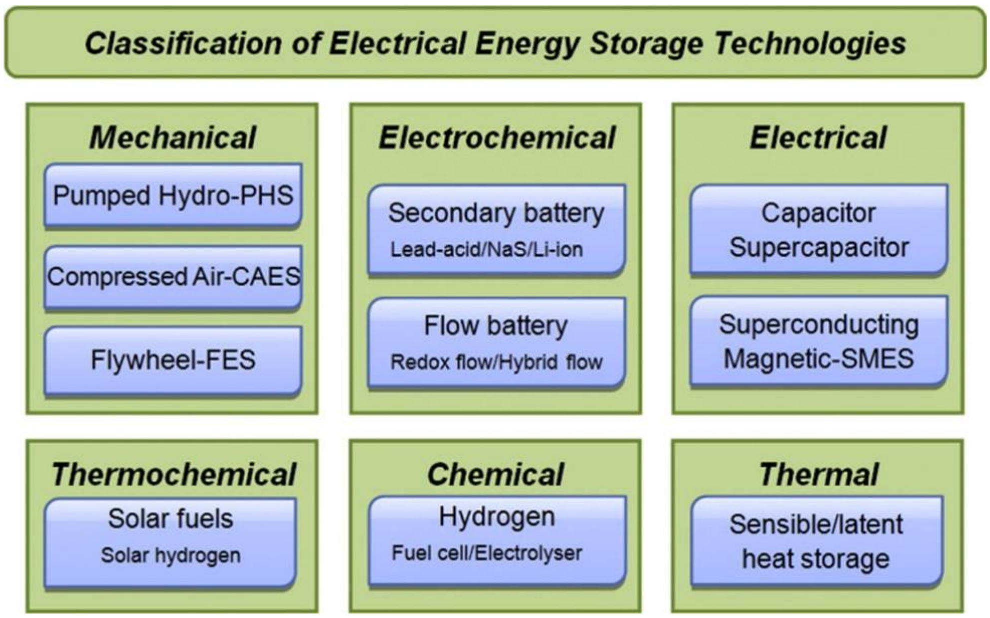

Figure 2. Classification of ESSs [19].

ESSs can be categorized into two types, high power and high energy density, according to their energy storage efficiency [20]. Higher-power storage systems are more responsive and can provide energy at a higher rate, but the power is available for a shorter period of time. High-energy-density ESSs, on the other hand, are capable of providing power for longer periods of time but have a slower response time. A hybrid energy storage system (HES) is a combination of two complementary ESSs with high energy density and high power density to provide relatively large storage capacity and fast charging and discharging rates. A common HES has a combination of batteries and supercapacitors, which utilize the higher energy density of batteries and the higher power density of supercapacitors to improve overall efficiency. ESSs or HESs are recognized as promising solutions for mitigating intermittent renewable energy sources and uncertain EV charging needs [21]. The storage capacity of an energy storage system is the total amount of energy that the system is capable of storing, usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh). The capacity of an energy storage system depends on a number of factors, including the design of the system, the type of battery, and the needs of the particular application. In addition, the charge and discharge rates of an energy storage system affect how quickly it can store and release energy. In practice, the capacity of an energy storage system is usually determined by the specific energy requirements and charge/discharge rates.

2.3. EV Charging Facilities

The growing global concern for environmental protection and sustainable transportation has led to a continued rise in the popularity and sales of EVs. They have become an integral part of modern transportation. EVs are categorized into hybrid, plug-in power, and fuel cell EVs based on the source of electricity used by the vehicle [22]. At the same time, the charging method of EVs has diversity. According to the charging technology, it can be divided into conductive charging, inductive charging, and battery charging [22]. In order to support the charging needs of EVs, the construction and development of charging facilities have become crucial. EV charging facilities are, in a way, "gas stations." This refers to the infrastructure that provides charging or switching services for EVs, including charging spots, charging stations, switching stations, etc. [23]. Charging spots are devices used to provide electric power to EVs and are usually installed in parking spaces or on walls that can be connected to EVs for charging. They can be categorized into alternating current charging spots (AC charging spots) and direct current fast charging spots (DC charging spots). The exact type depends on the type of power supplied and the charging speed. Generally speaking, a charging station is a facility that centralizes the management and provision of charging services. It usually features multiple charging posts to provide charging to multiple EVs at the same time. And it is typically located in locations such as public areas, commercial areas, or highway service areas and offers a variety of charging standards and power options to meet different models and needs of EVs. Figure 3 shows an EV charging at a charging station [24]. A switching station is another type of charging facility that provides quick replacement of EV batteries. At a battery exchange station, the battery of an EV can be quickly removed and replaced with an already-charged battery for fast charging and extended driving range. However, since the battery is owned by the battery exchange station, its charging cost is higher compared to other charging facilities. The architecture of a battery exchange station is shown in Figure 4 [25]. The construction and development of charging facilities are key elements in the popularization and diffusion of EVs. Therefore, governments, energy companies, and private enterprises are actively promoting the construction of EV charging facilities to meet the growing market demand for EVs.

Figure 3. EV charging at a charging station [24].

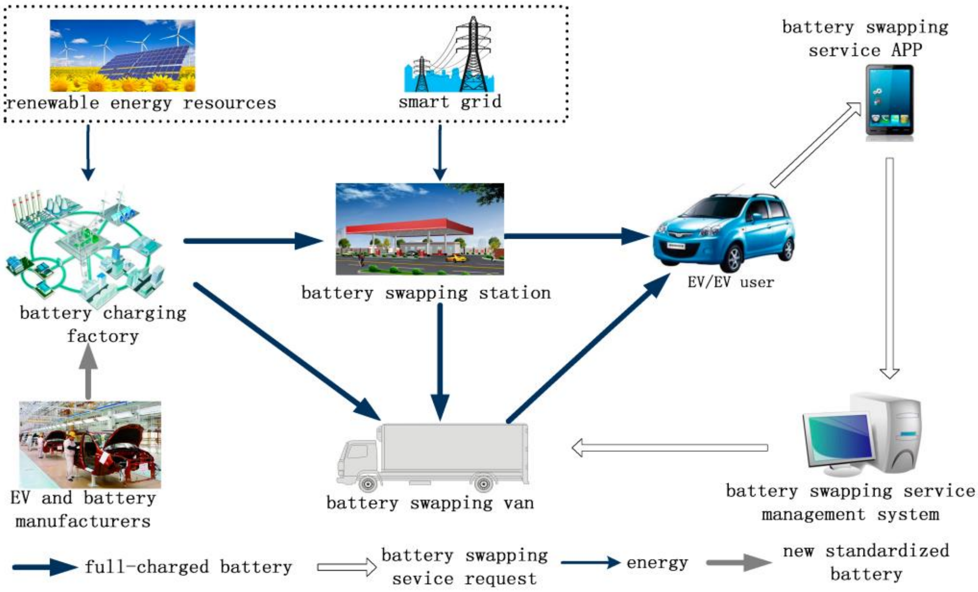

Figure 4. The architecture of a power exchange station [25].

3. Advantages and Challenges of Integrated PV and Storage Charging Stations

3.1. Strengths: Renewable Energy Utilization and Demand Response

The integrated PV and energy storage charging station refers to the combination of a solar PV power generation system, an ESS, and a charging station as a whole. It utilizes solar energy as a clean energy source for power generation, realizing the efficient utilization of solar energy and fast charging of EVs [26]. The system architecture of this new charging station is shown in Figure 5 [27]. One such technology, V2G (vehicle to grid), is a technology that enables electric vehicles to participate directly in the power system by allowing them to send current to the grid when their batteries need to be recharged or are fully charged. This two-way interaction is not limited to the charging process, but even when the EV is not in use, its battery can reverse the remaining controllable power to the grid, thus providing energy storage and support to the grid. Therefore, V2G technology is an integral part of the smart grid (SG), which helps to improve the stability and flexibility of the grid and provide better services to users. In this way, EVs can be used as a distributed power source to participate in the scheduling and management of the grid, further promoting the use and development of renewable energy. The SG is a concept that proposes an intelligent network of electrical microgrids that can be monitored, diagnosed, and rebalanced to improve efficiency. The aim of this is to avoid or minimize power outages. Unlike previously proposed grid systems that transmit power from the source of generation to the vehicle, the smart grid concept allows for bi-directional power transmission and communication [28]. The core components of an SG are advanced metering infrastructure (AMI), smart meters (SMs), and data collection units (DCUs) [29]. Significant difficulties are faced by SG technologies in the field of information and communication [30]. This new type of charging station, one of the most promising charging facilities, plays to its strengths in both renewable energy use and demand response. In terms of renewable energy utilization, it is able to utilize renewable energy sources such as solar energy for electrical energy generation. The excess electricity is then stored for subsequent use through energy storage technology. Such integrated charging stations can provide a stable and reliable supply of electricity, mitigating the randomness and uncertainty of renewable energy generation. They also reduce the dependence on the traditional grid and provide resilient support for grid loads, promoting the large-scale application of renewable energy. In addition, utilizing solar energy instead of the traditional coal- or oil-fired power generation methods can also reduce greenhouse gas emissions and be more friendly to the environment. In terms of demand response, energy supply and demand can be flexibly adjusted according to changes in grid demand. This reduces the demand for grid power by EVs and the impact on the grid load when charging EVs, and it ensures the security and stability of the grid system. Thus, in this regard, it offers the advantages of flexibility, peak and valley balancing, fast response capability, and reduced grid stress. Overall, integrated PV and storage charging stations offer significant advantages in terms of renewable energy utilization and demand response. They improve renewable energy utilization, smooth power fluctuations, and support demand response while having the ability to operate independently. This makes integrated PV and energy storage charging stations one of the most important facilities to drive renewable energy development and power system sustainability transformation.

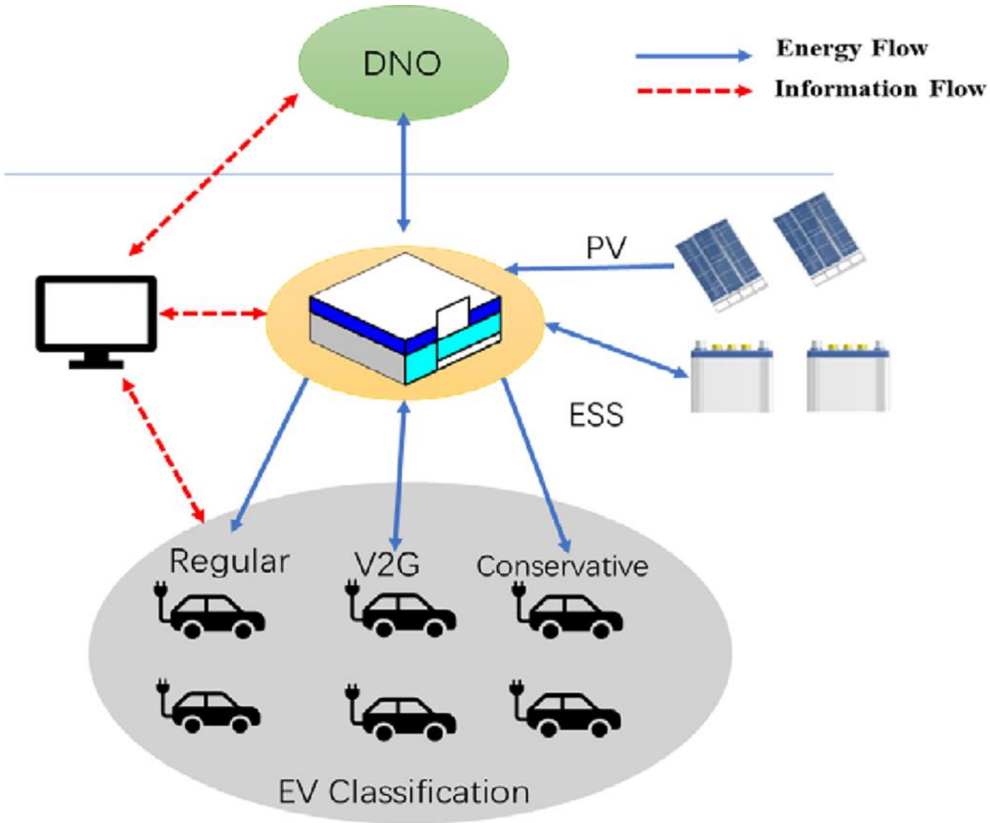

Figure 5. System architecture of integrated PV and energy storage charging stations [27].

3.2. Challenges: Capacity Allocation and Control Strategies

The integrated PV and energy storage charging station realizes the close coordination of the PV power generation system, ESS, and charging station. It has significant advantages in alleviating the uncertainty of renewable energy generation and improving grid stability. However, in practical terms, the inclusion of PV and ESS configurations is bound to increase the initial investment cost, making this new type of charging station not economically effective. Therefore, the rational configuration of PV, storage systems, and charging facilities for charging stations with integrated PV and storage is an effective measure to favor the economy of charging stations and reduce the initial investment cost.

For this new type of charging station, in addition to the need to consider the issue of its capacity configuration, it is also necessary to consider the control strategy of the entire system. PV power generation is characterized by intermittency and instability. In order to reasonably manage and balance the difference between charging demand and PV power generation, it is necessary to design and implement effective energy management strategies to ensure that the PV power generation system and the ESS operate in conjunction with each other to optimize energy utilization efficiency. Meanwhile, with the increase in the number of EVs, managing large-scale EV charging is also an important issue. At this time, the charging schedule at the charging station becomes crucial. Reasonable charging scheduling can satisfy the charging demand of users, balance the load of the power grid, and achieve the stability of the whole system. In addition, there may be fluctuations in the output power of the PV and storage charging stations due to changes in lighting conditions and uncertainty in user charging demand. By adjusting the power output of the PV power generation system and the charging power of the ESS, the fluctuations in PV power generation and charging can be smoothed, the impact on the grid can be reduced, and the stability of the grid can be improved. Large-scale, uncoordinated charging of EVs will increase peak loads on the grid during peak hours. Possible solutions are to strengthen the grid or shift peak electricity demand to off-peak hours.

In total, 2614 relevant papers on integrated PV and energy storage charging stations were retrieved from the Web of Science. Then, VOSviewer_1.6.19 software was utilized to draw the keyword network diagram, as shown in Figure 6. From the figure, it can be seen that the keyword clustering of the literature is divided into three categories, namely, storage system, charge and cost, which are represented by green, red and purple colors, respectively.

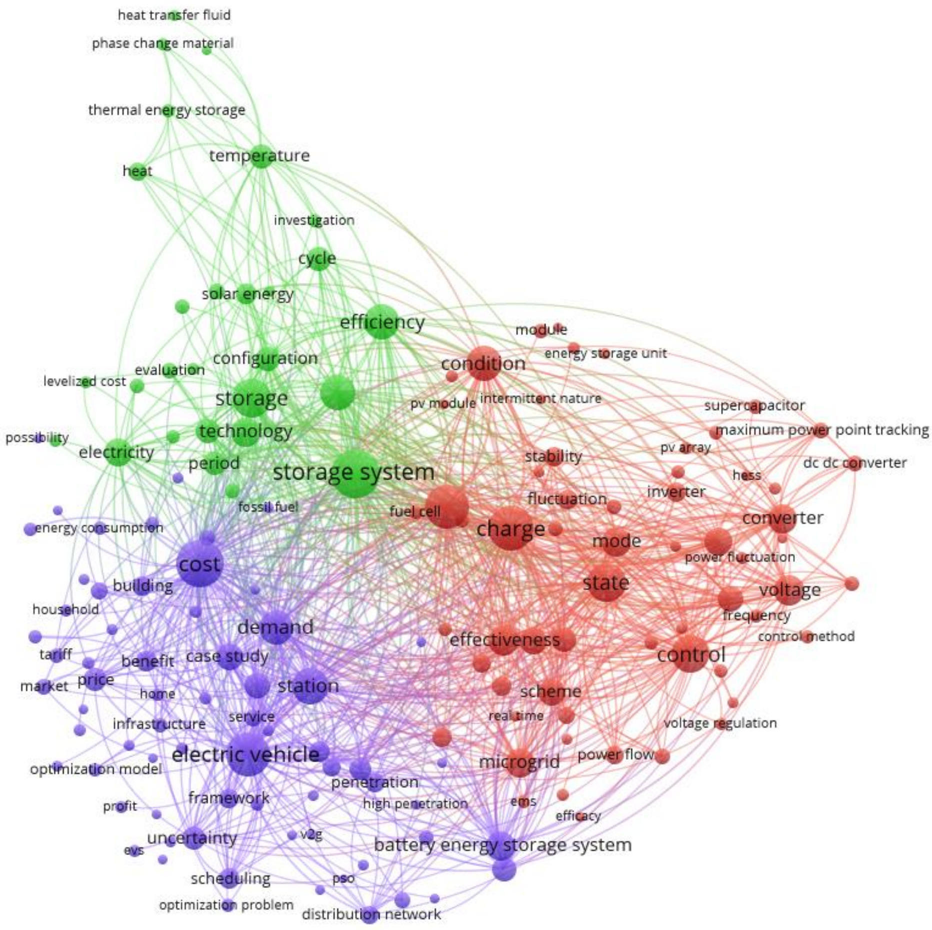

Figure 6. PV and energy storage charging stations keyword network diagram.

4. Capacity Allocation Methods and Algorithms

Photovoltaic (PV) power generation is a type of renewable energy generation. The use of a large number of PV systems not only reduces the use of fossil fuels but also reduces carbon dioxide emissions. Therefore, the continuous deployment of a large number of PV systems will turn out to be a trend. However, there are many problems with PV itself. For example, it can be affected by uncertainties such as weather and seasonal changes, resulting in greater volatility and instability in PV power output. In addition, when there is a surplus of PV power, there is again the problem of abandoned light and difficulties in connecting to the grid. Energy storage technology is able to solve the above problems to a large extent, so ESSs are often used in combination with PV systems. Due to the widespread popularity of EVs, many cities have already adopted this integrated PV and energy storage charging station for charging EVs. When establishing a charging station with integrated PV and energy storage in order to meet the charging demand of EVs while avoiding unreasonable investment and maximizing the economic benefits of the charging station, this requires full consideration of the capacity configuration of the PV, ESS, and charging stations. At present, there have been several scholars who have conducted extensive research on the capacity allocation of PV and energy storage EV charging stations.

The Web of Science search found 157 relevant kinds of literature on the capacity configuration of PV and energy storage charging stations. The keyword network diagram was drawn using VOSviewer_1.6.19 software and is shown in Figure 7. From the figure, it can be seen that the keyword clustering of the literature consists of four categories, namely, storage system, station, demand and energy storage capacity, which are represented in yellow, red, purple and green, respectively.

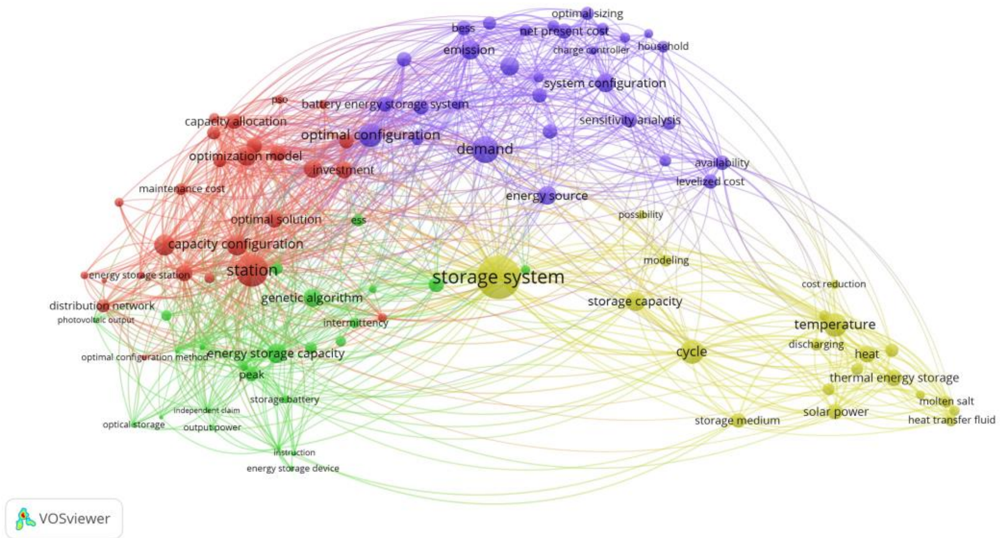

Figure 7. PV and energy storage charging station capacity configuration keyword network diagram.

4.1. PV System Capacity Configuration

It is found that the current literature on capacity allocation studies for hybrid PV and ESSs mainly focuses on studies on capacity allocation for ESSs. There are relatively few studies on capacity allocation for PV systems, and the studies on capacity allocation mainly consider economy and environmental protection. Moreover, intelligent optimization algorithms are mostly used to solve single-objective or multi-objective problems when solving capacity allocation problems. There are also some studies on the capacity allocation of PV systems, taking into account the size, power, and physical dimensions of the PV system as well as the point of common coupling (PCC) factors with the power system.

There are fewer studies on the capacity allocation of PV power systems, and these studies are mainly focused on multi-energy systems combining PV and other renewable energy sources. Intelligent optimization algorithms are introduced to solve the multi-objective optimization problem due to the complexity of their systems and their long computation times. These include Mahesh et al. [31] for a hybrid renewable energy system of PVs, wind, and batteries, which considered the demand for EVs and used an improved search space reduction algorithm in system sizing optimization to achieve the determination of optimal component capacity and efficient use of energy. Zhang et al. [32] used an improved genetic algorithm to solve the problem of multiple conflicting optimization objectives in capacity allocation for a multi-energy system with wind and PV-coupled hydrogen production. It has been verified that the method is superior to the traditional genetic algorithm and the hybrid particle swarm algorithm. Badea et al. [33] investigated a charging station based on a combination of PV power generation and ESSs using an improved genetic algorithm for optimal configuration of the PV system. The utilization of renewable energy and the sustainable charging of EVs were achieved. Zou et al. [34] proposed a stochastic simulation and weight sum method for the multi-objective optimization of PV cell systems, considering the uncertainty of building loads and PV generation. This method is more practical for solving the capacity allocation problem of the system. It is foreseeable that more and more complex multi-objective optimization problems for system capacity allocation can be solved with the help of new intelligent optimization algorithms due to different considerations and optimization objectives. However, the selection of different optimization algorithms needs to be based on the particular situation. Improved search space reduction and improved genetic algorithms, among others, are commonly used in PV system capacity allocation problems.

There is also consideration of the size, power, and physical dimensions of the PV system. A review of optimization techniques and objectives, component sizing systems, and different objective functions considered for designing hybrid renewable systems (HRESs) is presented in the literature [35]. The studies are divided into two categories, economic and technical, where economic criteria are mainly used to minimize costs and technical criteria include reliability, efficiency, and environmental objectives. A methodology for calculating the optimal size of a stand-alone PV array is presented in the literature [36]. Irradiance data recorded every hour of every day for 30 years were used to calculate the average power generation, and then the optimal number of cells and PV modules were calculated based on the minimum cost of the power system using a given load and the desired probability of power supply loss. Ammari et al. [37] provided an in-depth literature review on the four dimensions of HRESs: sizing, optimization, control, and energy management. The authors noted that with respect to dimensioning, the researchers used two basic methods, which are commercial software and conventional methods. In optimization, classical, manual, and hybrid methods are mainly used. Maximum power point tracking (MPPT) is the most commonly used control method. Energy management is mainly focused on techno-economic objectives.

The distance or connection between the solar panels and the point of common coupling (PCC) of the power system in a photovoltaic system mainly involves the following aspects: location of the solar panels, determination of the PCC, connection method, cable length, and layout. This concept is important for the design, installation, and operation of PV systems. Solar panel location refers to where the solar panels are installed in the PV system. Solar panels are usually mounted on the roof of a building, on the ground, or on other suitable sites to maximize the reception of solar radiation. In a PV system, connection means the distance or connection from the solar panel to the PV inverter in the PV system and the distance or connection from the PV inverter to the grid access point. The length and layout of the cables need to be considered when determining the distance between the solar panels, the PV inverter, and the power system. An increase in cable length increases the resistance of the system, which may lead to energy losses and a reduction in system efficiency.

4.2. Energy Storage System Capacity Configuration

In the problem of the capacity configuration of ESSs, a large number of studies are mainly aimed at meeting the charging demand of EVs, minimizing the economic cost, increasing the utilization of renewable energy sources, and maintaining the stability of grid voltage and power. It is a capacity configuration for a single ESS or an HES. Intelligent optimization algorithms have less complexity and computational effort than traditional optimization algorithms, so they are considered to be the most efficient way to solve many problems. Intelligent optimization algorithms, such as the hybrid particle swarm optimization algorithm, simulated annealing algorithm, compromise method, cat swarm optimization algorithm, genetic algorithm, etc., are widely used in solving the capacity allocation problem here. Table 1 summarizes the studies related to the capacity allocation of ESSs.

Table 1. Capacity allocation study of the energy storage system.

Ref.	Research Object	Consideration	Method/Technique	Goals/Solved Problems
[38]	HES with batteries and superconducting magnets	PV capacity and load	Hybrid particle swarm algorithms and hybrid compromise methods	Minimizing economic costs, waste PV, and load outages
[39]	ESSs in off-grid PV wind energy systems	Battery capacity, PV panel area, and wind turbine capacity	Simulated annealing algorithm	Reducing the unavailability and cost of different types of solar panel systems
[40]	Urban railway ESS	DC traction network voltage fluctuations	The multi-objective grasshopper optimization algorithm	Energy saving, voltage stabilization, and lower system costs
[41]	Grid-connected wind energy storage hybrid system	Constant tariffs and time-of-use tariffs	Cat swarm optimization	Minimize the total cost of the system
[42]	HESs	Cycle life operating characteristics of energy storage devices	Improved adaptive noise fully integrated empirical modal decomposition	Suppresses power fluctuations and reduces economic costs
[43]	Hybrid battery and ultracapacitor ESSs	Impact of supercapacitor quality on load power	Methods of dynamic programming	Optimal size results at the turning point
[44]	Battery storage system	In case of power failure	Probability distribution function	Reduce peak loads
[45]	High-power-density ESSs	Energy requirements for EVs	Artificial intelligence-based control methods	Extends battery life and reduces battery power fluctuations
[46]	Fixed ESSs for charging stations	Charging station size, grid-connected power, input data, and time resolution	Based on one year of data from four DC fast charging stations	Sizing the ESS
[47]	Hybrid systems for PV and energy storage	Time-sharing tariffs and charging and discharging strategies	Particle swarm optimization	Guaranteed supply of load demand and increase in economic efficiency
[48]	Battery storage systems for transformer thermal loads	High penetration of rooftop PV and time-sharing tariffs	Monte Carlo simulation	Reduced size of battery storage system
[49]	HESs	Real-time price demand response and distribution grid	Improved particle swarm optimization algorithm	Increased utilization of renewable energy
[50]	PV and ESSs	Different EV charging models and different tariff trends	Adaptive hybrid optimization algorithm	Optimal system capacity allocation and charging strategy
[38]	PV and ESSs	Based on a value chain perspective	Hybrid particle swarm algorithms and compromise methods	Minimum economic cost, abandoned PV, and load interruption rate
[51]	PV and battery storage systems	Number of PV panels and ESSs	Linear table quantization methods and genetic algorithms	Minimizing charging station costs and pollutant emissions

It is foreseeable that the current research on the issue of the capacity allocation of ESSs has produced relatively comprehensive research results from multiple perspectives, considering multiple factors and using multiple methods. The optimal ESS capacity allocation scheme is developed by comprehensively considering the charging demand, ESS performance, cost-effectiveness, and optimization algorithm. It is used to meet EV charging demand and maximize economic benefits.

In addition, for the ESS capacity allocation problem, some researchers consider the interconnection to the power system. In the literature [52], a methodology that takes into account climate parameters and examines demographics is used. Several key aspects related to the integration of renewable energy sources and EV charging stations into the grid were comprehensively analyzed. These include the design and management of multiple microgrids, the impact of EV charging stations on the grid (e.g., load shifting, peak shaving, and system stabilization), and the technical difficulties of integrating EVs into the grid. In the literature [53], the behavior of systems with high penetration of renewable energy sources is studied. It was concluded that the system is stable when the interconnection is realized under the conditions of appropriate location and dynamic component parameters. The critical eigenvalues of the system increased with the increase in renewable energy sources. Alves et al. [54] presented a scenario considering the interconnection of isolated power systems, with the objective of increasing the share of renewable energy sources in total electricity production. The results show that by 2030, the penetration of renewable energy sources will increase by 50 percent compared to the current scenario. The realization of this scenario requires an additional cost of about 1.29 MV per year. Aourir et al. [55] investigated the hybrid control problem for a grid-connected photovoltaic system with active filtering capability in a highly distorted grid. The interface system used consists of a multilevel topology that provides better performance in terms of power quality improvement compared to a two-level topology, especially for single-level PV systems. The interconnection of distributed or renewable generation systems (RPGs) to the grid must fulfill the standard requirements for voltage support, frequency support, low voltage ride-through, and current harmonics [56]. The large amount of power injected into the utility grid by renewable generation systems can significantly affect the grid voltage. Providing voltage and frequency support through active and reactive power control must address both steady-state and dynamic network operations [57].

4.3. Capacity Configuration of Integrated PV and Energy Storage Charging Stations

A large number of studies have been conducted on the capacity configuration of this new type of EV charging station. These studies have focused on the investment and operating costs of charging stations, PV output instability, EV charging and discharging demand, time-of-use tariffs, system security, carbon emissions, and impacts on grid voltage and power, as well as power quality. Intelligent optimization algorithms such as the improved differential evolution method algorithm, the grey wolf optimization algorithm, the multi-intelligent particle swarm optimization algorithm, the machine learning method, and the improved simulated annealing algorithm are utilized to establish mixed-integer nonlinear planning models, single- and double-layer optimization models, etc.

Ahmad et al. [58] controlled the charging and discharging of a battery energy storage system (BESS) by applying an energy management strategy, a vehicle-to-grid (V2G) strategy. The Monte Carlo method was utilized to solve the uncertainty of EV charging and PV power generation. The optimal location and capacity of charging stations were analyzed in terms of charging station investment costs, plug-in EV users, and distribution grid operators. Ji et al. [59] conducted experiments on real EV historical data from 297 users of an EV rental company. Considering multiple factors such as construction cost, solar energy fluctuation, and user demand, an efficient method for deciding the location and size of solar-assisted charging stations was proposed. The results show that the method is able to produce high-quality decisions in a reasonable amount of time. Abuelrub et al. [60] utilized EVs as a temporary ESS. The economic effects of considering the investment costs of charging stations, electricity prices, and incentives for vehicle owners in a microgrid integrated with PV power plants were investigated. A planning algorithm was used to obtain the number of EV charging stations required to maximize the profit of the system. Castro et al. [61] developed a model to predict the energy consumption and power demand of EV fast charging stations based on the logistic growth method. It provides a basis for the planning and configuration of charging stations and incorporates PV generation and ESSs, which are used to minimize the impact on the grid. Dai et al. [62] proposed a multi-intelligent particle swarm optimization (MAPOS) algorithm for the optimal design of an integrated light storage and charging station. The objective was to minimize operating costs and carbon emissions and determine the optimal capacity configuration of the charging station. Li et al. [63] proposed an optimal capacity allocation model for a photovoltaic energy storage charging station (PV-ESS-CS). The model takes into account the uncertainty of EV charging and discharging demand and PV output and uses conditional value at risk to measure the risk of a low return to maximize the return after considering this risk. Liu et al. [64] proposed a combined PV, energy storage, and EV optimization model based on cumulative prospect theory (CPT) and the multi-objective particle swarm optimization (MOPSO) algorithm. Sustainability factors were considered from economic, social, and environmental perspectives. Liu et al. [65] proposed a two-tier optimization model for PV storage charging station capacity allocation, considering user utility and tariff pricing based on user behavior. This two-layer optimization model provides a more economical and reasonable planning scheme than the single-layer optimization model, which can reduce the investment cost by 8.84%, reduce the operation and maintenance cost by 13.23%, and increase the net income by 5.11%. Pan et al. [66] proposed a capacity allocation method based on a historical data-driven search algorithm for PV and BESS integrated charging stations (PES-CS). The method determines the capacity ratios of PV and BESS by analyzing actual operation data to achieve the goal of maximizing economic efficiency. Wei et al. [67] proposed a data-driven optimal design framework for EV charging microgrids (EVCMs) based on photovoltaic–battery hybrid energy storage systems. Historical data and machine learning methods were utilized to predict future PV generation, load demand, and electricity prices. The capacity and operation strategy of PV-BESS were optimized by a mixed-integer linear programming (MILP) model to maximize the economic and environmental benefits. Hishimwe H. et al. [68] proposed an optimization framework for profit maximization. Vehicle arrival patterns, intermittent PV generation, and ESS management were integrated. Joint planning and operation of charging stations were determined to find an optimal configuration of a grid-connected charging station and optimal power scheduling of the charging stations during operation. Yi et al. [69] modeled the determination of charging stations and energy storage capacity for EVs. Factors affecting efficiency and system safety were considered, and the charging scheduling plan was optimized using an improved simulated annealing algorithm.

The variable input of multiple renewable energy sources exacerbates power quality and grid stability problems. The problems of power quality mainly include current harmonics, frequency deviation from the nominal value, voltage fluctuation, and power deviation. Yang et al. [70] investigated and developed a flexible power controller configured in a photovoltaic inverter, which enables switching from one mode to another during operation. The control strategy is based on the single-phase PQ theory, which provides the possibility of generating a suitable reference point for the internal current control loop. Badoni et al. [71] proposed a three-phase shunt active power filter (SAPF) for mitigating power quality problems. Both unit power factor and voltage regulation modes mitigate power quality problems such as harmonics, reactive power, and load imbalance. Romero-Cadaval et al. [72] stated that the control functions in the field of control schemes include internal current/power and external dc-link control, maximum power point tracking (MPPT), monitoring and grid synchronization, proper operation in heavily distorted grids, islanding/anti-islanding operation, active power feed-forward, active/reactive external control loops to support the power system, etc.

5. Control Strategy of the System

Regarding the control strategies of integrated PV and storage charging station systems, the existing studies can be broadly categorized into several aspects of control, including EV control strategies, energy management, charging scheduling and strategy, grid stability, and power management. The Web of Science search found 751 relevant kinds of literature on control strategies for PV and energy storage charging station systems. The keyword network diagram was drawn using VOSviewer_1.6.19 software and is shown in Figure 8. From the figure, it can be seen that the keyword clustering of the literature consists of four categories, namely, cost, voltage, battery energy storage system and energy source, which are represented in purple, red, green and yellow, respectively.

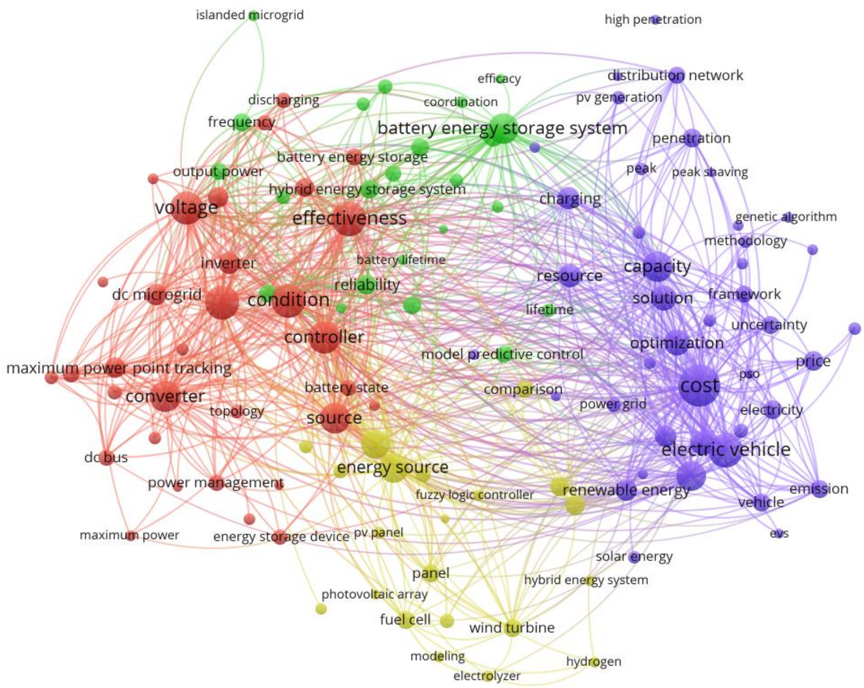

Figure 8. PV and energy storage charging station system control strategy keyword network diagram.

5.1. EV Control Strategies

Electric vehicle control strategies are methods and techniques for intelligently controlling the various systems and components of an electric vehicle. These strategies are designed to achieve multiple objectives, including improving vehicle performance, extending battery life, increasing energy efficiency, enhancing safety, and providing a better driving experience for the driver. Some of the common control strategies include motor control, battery management systems, brake energy recovery, drive force distribution, intelligent energy management, vehicle stability control, driving mode selection, and charging control.

Liu et al. [73] proposed a three-heat-source segmented heating control strategy to reduce the heating energy consumption of an electric vehicle, where the three heat sources denote the motor waste heat, air, and positive temperature coefficient (PTC) heater. Compared with the conventional strategy, the proposed control strategy can reduce energy consumption by 18.49% when operated at a -10 °C ambient temperature for 2.5 h. Nie et al. [74] proposed a hierarchical optimal control strategy for a group of intelligent fuel cell hybrid electric vehicles (FCHEVs) in a network-connected environment. The hierarchical control framework consists of upper-speed regulation and lower power allocation. Simulation results based on complex road conditions show that the proposed controller has good energy economy and tracking performance. Ren et al. [75] proposed a predictive control strategy for battery-life-aware energy management based on a deep reinforcement learning algorithm predictive equivalent consumption minimization strategy (DRL-PECMS).

The demand power is first predicted using a back-propagation neural network, and then the deep reinforcement learning algorithm is used to optimize the battery power, which effectively optimizes the trade-off between energy consumption and battery durability performance. Li et al. [76] developed a three-input, single-output fuzzy controller for distributing hydraulic and electric braking forces, taking into account the effects of braking intensity, vehicle speed, and battery SOC on regenerative braking performance. It was used to examine the efficiency and safety of regenerative braking energy recovery systems for electric vehicles. Ma et al. [77] proposed an Ant Colony Optimization–Fuzzy Sliding Mode Control (ACO-FSMC) hierarchical strategy for battery thermal management systems (BTMSs) in electric vehicles. Ant Colony Optimization (ACO) is used in the upper layer of the controller to solve the reference speed of the pump and compressor, and Fuzzy Sliding Mode Control (FSMC) is used in the lower layer to control the speed of the pump and compressor. Xue et al. [78] proposed a novel dual-motor powertrain system including two motors and transmissions for nine combined gears. It was used to solve the problem of interrupted shift power supply in electric vehicles with mechanical automatic transmissions. Liu et al. [79] proposed a coordinated control strategy for braking and gear shifting in an electric vehicle equipped with a two-speed automatic transmission. The coordinated control strategy mainly consists of braking force distribution and synthetic shift regulation for braking operation. Liu et al. [80] proposed an EV drive system control method based on EV energy consumption and battery life. The EV driving state was combined with motor control, and a global control strategy for the EV drive system based on an optimized acceleration profile was proposed. Bayati et al. [81] considered a commonly used power electronic topology and discussed in detail the trade-offs and constraints of electric vehicle battery chargers in terms of cost, size, weight, conduction losses, switching losses, microcontrollers, isolation, voltage and current levels, voltage and current ripples, battery specifications, charging and discharging algorithms, control systems, switched-gate drivers, and efficiency.

5.2. Energy Management

In order to realize the efficient distribution of energy and the satisfaction of charging demand, some scholars have proposed optimal strategies regarding the trading aspect of electric energy. Energy trading between electric vehicle charging stations is achieved by proposing a two-tier energy trading market framework. Minimizing power input and maximizing operator profit are also achieved by proposing a two-tier stochastic energy trading model for technical virtual power plants. The uncertainty of EV charging demand and the intermittent and fluctuating nature of PV power generation are also taken into account. Real-time data and forward-looking predictions further improved the charging station's energy utilization efficiency, user satisfaction, and support for the grid. There are also some controls for the ESS, with considerations that include, among other things, extending the life of the storage system and reducing system costs. This is mainly achieved by proposing a battery life loss modeling and anti-aging energy management method and an optimal energy management strategy. Weights are assigned to battery capacity degradation and energy loss based on the control strategy. An optimization algorithm is used to solve the problem to achieve the objectives of reducing fuel costs and mitigating battery aging. In the home energy management segment, it is mainly used to coordinate charging and discharging schedules for power generation systems, EVs, ESSs, and other loads, minimizing household electricity costs and maximizing PV consumption by proposing optimization and energy management strategies, etc. Large-scale, uncoordinated charging of EVs will increase peak loads on the grid during peak hours, and possible solutions are to strengthen the grid or shift peak electricity demand to off-peak hours. Coordinated charging uses load shifting or valley charging strategies based on time-varying tariffs (time-of-use tariff systems) to actively include EVs in the demand response process. In addition, many other researchers have applied advanced intelligent optimization algorithms and machine learning algorithms to solve the energy management strategy problem. Table 2 summarizes relevant studies in energy management.

Table 2. Energy management studies.

Ref.	Consideration	Research Object	Method/Technique	Goals/Solved Problems
[82,83]	Electricity trading	■ EV charging stations and EVs ■ Virtual power plant	■ Two-tier energy trading market framework ■ A two-level stochastic trading model	■ Energy trading between charging stations ■ Minimized power trading
[84–91]	Uncertainty in PV generation and charging demand	■ EV charging station ■ PV and energy storage charging stations ■ ESSs and EVs ■ Electric buses with PV and energy storage ■ Solar PV on-board EV charging system ■ The distribution system consists of 4 microgrids ■ EV charging stations with integrated PV ■ Plug-in EV ESSs	■ Mixed-integer linear programming ■ Display model predictive control methods ■ Supervised learning approach ■ Three-tier stochastic energy management approach ■ Model predictive control without voltage sensors ■ Stochastic techniques and linear programming ■ Discrete stochastic control methods ■ Stochastic control methods	■ Implementation of energy management ■ Implementation of energy management ■ Reduced energy costs and improved operational efficiency ■ Reduces operating costs and maintains voltage stability ■ Fast response and low power oscillations in steady state ■ Reducing the operating costs of microgrids ■ Reduced energy exchange between the grid and charging stations ■ Energy scheduling and optimization
[92–95]	Control of ESSs	■ EV battery storage system ■ Hybrid battery and ultracapacitor ESSs ■ HESs for EVs ■ HESs for EVs	■ Quantitative modeling of multifactor battery life loss ■ Pontryagin-based optimal energy management strategy ■ New optimization method for energy distribution ■ A new approach to energy management	■ Quantifying and reducing battery aging costs ■ Minimize power usage and maximize battery life ■ Improved battery capacity degradation and energy loss ■ Reducing fuel costs and mitigating battery aging
[96–98]	Home energy management	■ Smart home optimization and energy management ■ Home energy management ■ Residential energy management	■ Mixed-integer linear programming model ■ Energy management control system ■ Combination of rule-based methods and heuristic optimization	■ Minimizing the cost of electricity for consumers ■ Minimizing household electricity costs and maximizing PV consumption ■ Reduction in total electricity purchased from utility companies

Table 2. *Cont.*

Ref.	Consideration	Research Object	Method/Technique	Goals/Solved Problems
[49,99–105]	Load shifting	■ EVs	■ Valley filling strategy	■ Suppression of grid peaking loads
		■ Microgrid (MG) systems from HESS	■ Orderly charging and discharging strategy for electric vehicles	■ Reduced operating costs and peak-to-valley load variance
		■ Smart charging station	■ PV and V2G power supply	■ Improving grid stability during peak load hours
		■ Charging and discharging systems	■ Two-stage optimization strategy for charging and discharging	■ Grid-side and customer-side "win–win" benefits
		■ EVs	■ Aggregator-based demand response (DR) mechanism	■ Grid cost savings and peak-to-valley difference reduction
		■ EVs	■ A two-layer deep learning model	■ Increase profits and reduce the cost of charging electric vehicles
		■ EVs	■ Variable power charging strategy	■ Significant increase in acceptability
		■ State of charge	■ Levelized cost of energy (LCOE)	■ Reduce costs and pollution associated with the charging process
[106–111]	Using advanced intelligent optimization algorithms	■ HESs ■ Hybrid EVs ■ HESs for EVs ■ Virtual energy hub ■ HESs for EVs ■ Large EV charging station	■ Deep reinforcement learning for soft actor–critics ■ Multi-intelligence reinforcement learning ■ Genetic algorithm ■ Game theory and distributed optimization algorithms ■ Fuzzy logic controllers and Markov chain models ■ Fuzzy logic controllers and artificial neural networks	■ Minimizing energy losses in HESs ■ Efficient use of energy ■ Minimal energy loss ■ Improved system economy and reliability ■ Suppression of peak battery current ■ Minimize operating costs and carbon emissions

5.3. Charge Scheduling and Strategy

Charging stations are designed to achieve optimal energy utilization and meet user needs and grid requirements. Electricity generated by PV power generation can be used for a variety of purposes, such as charging EVs, grid support, and battery storage. By dynamically scheduling the distribution of this energy, optimal energy utilization and system efficiency can be achieved. Based on the uncertainty of charging demand and PV generation, Yang et al. [112] proposed a robust model predictive control (R-MPC)-based charging scheduling method for EVs. The method is used to solve the mixed-integer non-linear programming (MINLP) scheduling problem embedded with solar power generation and charging demand models. Experiments show that the scheduling method is able to obtain optimal profits under high uncertainty. Zhong et al. [113] considered the uncertainty of sources and loads and improved the economy and reliability of the distribution network by coordinating and optimizing the scheduling of source–load–storage.

PV energy storage charging stations are usually equipped with energy management systems and intelligent control algorithms. The aim is for them to be used for detecting and predicting energy production and consumption and for scheduling charging and allocating energy based on the optimization results of the algorithms. Paterakis et al. [114] used smart grid technology and optimization algorithms to achieve the cooperative operation of a smart home domain consisting of EVs, energy storage, and distributed generation. Gao et al. [115] investigated the optimal operation mode of a PV–battery storage system power plant, considered typical scenarios, and proposed an integrated scheduling strategy based on an optimization method. The aim was to achieve efficient operation and energy utilization of the power plant. Jiang et al. [116] proposed an improved binary gray wolf optimizer (IBGWO) for solving the charging scheduling problem. A real-time charging scheduling strategy was designed based on short-term PV power prediction, and the effectiveness of the strategy was verified by simulation results. Long et al. [117] studied the integrated operation mode of wind and energy storage based on a smart microgrid with multi-intelligent interaction and proposed the corresponding operation strategy and optimization method. The efficient operation and optimized energy utilization of the smart microgrid were achieved. Yan et al. [118] proposed a four-stage intelligent optimization and control algorithm. The method was used to optimize the operational scheduling of an EV two-way charging station equipped with PV generation and stationary battery storage systems integrated with a commercial building. The aim was to minimize the operational costs involving customer satisfaction while taking into account potential uncertainties. Yang et al. [119] used the Benders decomposition method to achieve coordination between a solar PV system and an EV charging station. This approach solves the energy supply problem of the charging station, improves the utilization of the PV system, and achieves an energy contribution to the grid while meeting the charging needs of EVs. Yao et al. [120] designed a system that utilizes PV power generation and an ESS to provide charging and discharging for EVs. The charging and discharging schedules of each EV, as well as the power scheduling of the grid and the ESS, were optimized by a mixed-integer linear programming (MILP) method. Maximum utilization of PV power and minimization of operating costs were achieved. Abdelghany et al. [121] proposed a coordinated and optimized operation strategy for a grid-connected wind microgrid based on an HES. The economic cost, operational cost, and degradation issues of the ESS, as well as the physical and dynamic constraints of the system, were considered. Experiments show that the proposed strategy is able to satisfy the constraints and energy requirements while reducing the equipment cost and extending the battery life. Saldana et al. [122] proposed an aging model for nickel–manganese–cobalt (NMC) batteries for commercial EVs based on experimental data. The effects of different temperatures, states of charge, and aging times on battery performance were analyzed, and an optimized charging strategy was proposed. It can prolong the service life of the battery and improve its efficiency.

Some other scholars have taken a different approach to scheduling by taking into account time-sharing tariff factors. Aznavi et al. [123] proposed a point-to-point operational strategy based on photovoltaic-equipped office buildings and charging stations, considering EV energy pricing in order to share energy and maximize economic benefits. Schwarz et al. [124] investigated the effects of integrating EVs and ESSs with solar PV under different electricity pricing strategies and proposed a scheduling and optimization strategy based on electricity pricing. The strategy maximizes the utilization of solar PV power and the overall system economics, providing a potential solution for the large-scale application of renewable energy. Yang et al. [125] introduced a charging station energy management strategy based on time-of-use tariffs. A comprehensive benefits analysis model for charging stations was proposed from the perspective of PV storage charging stations, the grid, and the social multi-beneficiaries.

5.4. Grid Stability

Integrated PV and energy storage charging stations have an impact on the stability of the power grid. Suitable design and control strategies are needed to minimize the potential impacts and improve the stability of the grid. Electric vehicles can put a strain on the power system because, when charging from the grid, they behave as nonlinear loads with different characteristics from typical loads and can consume large amounts of power quickly. The current research of some scholars in this area includes mainly grid stability evaluation and improving grid stability and reliability by reducing peak load or power demand. In particular, the impact of photovoltaic systems on the grid stability of charging stations is investigated through steady-state stability assessment, and relevant assessment methods and indicators are proposed. Methods for reducing peak power demand and storing solar energy include proposing charging strategies for electric vehicles. There are also multi-objective probabilistic optimization power flow algorithms based on agent models for power system reliability and sustainability optimization. There is also the use of hierarchical control methods and coordinated control strategies to ensure grid frequency and voltage stability and improve the efficiency of distributed new energy sources. Moreover, efficient energy management methods are proposed to maximize the benefits of charging facilities and minimize losses in the distribution network. Table 3 summarizes the studies on grid stability.

Table 3. Grid stability studies.

Ref.	Research Object	Consideration	Method/Technique	Goals/Solved Problems
[126]	PV AC bus plug-in EV charging station	Interactions between subsystems often lead to instability problems	A modified infinity one-norm (MION) stability criterion based on the impedance method	Evaluating the stability of AC bus EV charging stations with PV
[127]	EVs and PV power	Different charging places and charging times	EV charging strategies	Reducing peak power demand and storing solar energy
[128]	Distribution networks for PV power generation and EVs	Uncertainty in solar PV generation, EV charging demand, and household appliance loads	A surrogate-assisted multi-objective probabilistic optimal power flow (POPF)	Achieving optimization of power system reliability and sustainability
[129]	Renewable energy, ESSs, and DC microgrids for EV stations	Hierarchical control problems for EV charging stations	Hierarchical control method	Stabilizes frequency fluctuations and regulates DC bus voltage
[130]	EVs and mobile ESSs	Overvoltage limitation due to distributed power sources and domestic EVs in distribution networks	A multi-scenario and multi-objective co-optimization approach for distributed power grids	Increasing PV consumption capacity and improving voltage limitations
[131]	PV, energy storage systems, and EVs	Bi-directional currents manage the load distribution, taking appropriate coordination through the controller	Layered coordination framework	Significantly lower domestic load demand on the distribution network during peak hours
[132]	PV, battery storage, and EVs	Read load data from smart meters in real time and take appropriate coordination measures using the controller	Improved decision tree algorithm	Reducing peak demand on the distribution grid
[133]	Solar EV battery charging facility	Uncertainty in home PV systems and EV charging	Uncertainty in home PV systems and EV charging	Uncertainty in home PV systems and EV charging
[134]	PV and ESSs	Different control strategies for PV and ESSs	Coordinated control strategy for flexible DC systems	Ensuring grid frequency and voltage stability
[135]	EV charging process	Power consumption, time, and location of electric vehicles	Peak Load Management Model (PLM)	Maintaining smart grid stability
[136]	EV mobile energy	Mobility in electric vehicles	Capacity assessment model for electricity supply	The weakest areas of coupled energy networks have many commonalities
[137]	EVs	Uncertain behavior of loads	Probabilistic approach	Evaluation of harmonics and voltage unbalanced levels
[138]	Electric transport	Charging uncertainty	Methods of analyzing power quality	Transformer overloading is a serious problem
[139]	EVs	Charging uncertainty	An uncertainty quantification algorithm for Polynomial Chaos Expansion (PCE)	Enabling rapid uncertainty quantification
[140]	EVs	Steady-state computational modeling assessment	Charge management and control methods	Reducing the negative impact of charging on the grid

5.5. Power Management

The power management of PV storage charging stations is the energy flow and control between the PV power generation system, ESS, and EV charging demand. Reasonable power management strategies and techniques can maximize the use of renewable energy, meet charging demand, reduce the power consumption of the grid, and maximize the economic benefits of the system. In terms of power control, Prasertde et al. [141] proposed an algorithmic optimization-based selector controller design and power management method for an EV fast charging station with a hybrid PV–fuel cell source and ESS. The aim was to rationally allocate the power of PV, fuel cells, and the grid according to the different energy demands of EVs to minimize grid power consumption and maximize trading revenue. Zheng et al. [142] introduced partial power processing in a solid-state transformer to realize multi-port control of PV, energy storage, and fast-charging EVs, improving energy conversion efficiency and charging system integration. Chandra et al. [143] proposed an energy management scheme for controlling the power flow between rooftop PV arrays, EVs, ESSs, and residential AC loads, as well as considering their respective states of charge. A multi-scenario evaluation of a grid-connected residential EV charging station using a rooftop PV solar system and a battery as an ESS is presented. García-Trivino et al. [144] proposed a new decentralized energy management system (EMS) for the control and operation of medium-voltage DC microgrids. Efficient power management and energy utilization are achieved by effectively coordinating the power flow between PV systems, ESSs, and EV charging loads. Chen et al. [145] proposed a model predictive control (MPC)-based energy management strategy (EMS) for a hybrid battery and an ultracapacitor ESS for EVs. The strategy takes stabilizing the DC bus voltage and improving the system efficiency as the two main optimization objectives.

The control strategies and algorithms for photovoltaic (PV) systems are mainly aimed at optimizing the work of the solar panels to maximize their energy output and ensure the safe and stable operation of the system. These strategies and algorithms cover a wide range of aspects, including maximum power point tracking (MPPT), feedback control, voltage/current regulation, and more. The MPPT algorithm is a key part of PV system control. MPPT algorithms can be classified into two broad categories: traditional and modern methods. The traditional approach is the simple MPPT algorithm, which has been widely used from the beginning. In particular, this includes the Perturb-and-Observe (P&O) and Incremental Conductance (InC), as well as Hill Climbing (HC), Fractional Open-Circuit Voltage (FOV), and Fractional Short-Circuit Current (FSC). Modern approaches include a variety of progressive MPPT control and optimization algorithms and methods, including fuzzy logic control (FLC), automatic control systems (ACSs), artificial neural networks (ANNs), genetic algorithms (GAs), and swarm intelligence (SI) methods. Raiker et al. [146] used a boost converter to connect the PV array interface to the power system for current control and utilized a momentum-based P&O MPPT technique to achieve maximum power point tracking of the PV array. Ahmed et al. [147] used the incremental conductivity method as part of MPPT and combined a hybrid optimization approach (Crow-Pattern Search) and an ANFIS-based method. It was investigated to achieve more efficient power capture and optimize the system performance under different environmental conditions. M.S. et al. [148] introduced a novel MPPT algorithm for PV systems using an adaptive step-climbing method based on fuzzy logic. The algorithm adjusts the step size of the step-climbing algorithm through fuzzy logic to adapt to different operating conditions, aiming to improve the energy capture efficiency and performance of the PV system. Hmidet et al. [149] proposed a simple and efficient off-grid SPV pumping system (SPVWPS) using a control strategy that associates a modified FOV method with MPPT and closed-loop scalar control. Babes et al. [150] proposed a meta-heuristic-optimized multi-layer feed-forward ANN controller for extracting maximum power from available solar energy for a three-phase shunt active power filter (APF) grid-connected PV system powering an arc welder. Ali et al. [151] proposed two artificial intelligence-based maximum power point tracking systems for grid-connected photovoltaic units, namely optimization-based fuzzy logic control using genetic algorithms and particle swarm optimization and artificial neural networks relying on genetic algorithms.

6. Conclusions

This study examines the concepts related to integrated PV and energy storage charging stations, with an emphasis on outlining research on their capacity configuration and system control strategies. Integrated PV and energy storage charging stations are integrated energy systems that combine PV systems, ESSs, and charging stations. They can not only provide clean energy for EV charging but also achieve a number of auxiliary services such as peak shaving and valley filling, alleviating the pressure of electricity consumption, and so on. This improves the operational efficiency of the system to a large extent. The main function of the ESS is to store the electricity generated by PV power generation or to store the electricity when the electricity price is low. The stored energy is then released to meet the charging demand during peak loads or peak tariffs. It maximizes the economic benefits of the charging station by taking advantage of peak and valley price differences and renewable energy.

Considering the uncertainty in the charging demand of both PV power generation and EVs, this paper focuses on an overview of their capacity configurations and control strategies for the system. It is found that the current research on capacity allocation is mainly focused on the capacity allocation of ESSs, and there are fewer studies on PV systems. There are even fewer studies that consider both energy storage and PV systems. Most of the studies consider the economy and environmental friendliness of the system. Intelligent optimization algorithms are mostly adopted in the solution of capacity allocation problems, for example, an improved search space reduction method, an improved genetic algorithm, a hybrid particle swarm algorithm, a simulated annealing algorithm, a grey wolf optimization algorithm, a cat swarm optimization algorithm, a machine learning method, and so on.

Control strategy research can be categorized into several areas, such as EV control strategies, energy management control, charging scheduling and strategies, grid stability, and power management. Electric vehicle control strategies are methods and techniques for intelligently controlling various systems and components of electric vehicles. These strategies are designed to achieve a variety of goals, including improving vehicle performance, extending battery life, increasing energy efficiency, enhancing safety, and providing a better driving experience for the driver. Some common control strategies include motor control, battery management systems, brake energy recovery, drive force distribution, intelligent energy management, vehicle stability control, driving mode selection, and charging control. In terms of energy management, power trading strategies are proposed, and methods such as real-time management, model predictive control, and stochastic control are adopted for energy. Some scholars control the ESS with the aim of minimizing the loss of batteries, prolonging their service life, and reducing the cost of the system. The control strategies and algorithms for PV systems are mainly aimed at optimizing the operation of solar panels to maximize their energy output and ensure safe and stable system operation. The strategies and algorithms involved include MPPT, feedback control, voltage/current regulation, and so on. Among them, the MPPT algorithm is a key part of PV system control. As large-scale, uncoordinated charging of EVs will increase peak loads on the grid during peak hours, it may be possible to achieve peak load shifting by strengthening the grid or shifting peak electricity demand to off-peak hours. In charging scheduling and strategy, based on the uncertainty of charging demand and PV generation, a charging predictive scheduling model and an intelligent control algorithm are proposed for monitoring and scheduling energy allocation. There are also some considerations of time-of-day tariffs and different scheduling methods. Research in the area of grid stability mainly includes the evaluation of grid stability and the improvement in grid stability and reliability by reducing peak load or power demand. In terms of power management, the main focus is to reasonably allocate the power of PV, storage systems, and the grid to minimize grid power consumption and maximize trading revenue.

Through the study of capacity allocation and control strategies for charging stations with integrated PV and energy storage, it was found that the use of more accurate PV generation forecasts and charging load forecasts enables the refinement of capacity allocation. At the same time, the use of well-established and intelligent methods in control strategies can better respond to complex and changing demand and grid conditions. It has been found that the coupling relationship between capacity configuration and system control strategy is not close enough, which is also the focus of future research.

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