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Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings

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Abstract

Solar energy is globally promoted as an effective alternative power source to fossil fuels because of its easy accessibility and environmental benefit. Solar photovoltaic applications are promising alternative approaches for power supply to buildings, which dominate energy consumption in most urban areas. To compensate for the fluctuating and unpredictable features of solar photovoltaic power generation, electrical energy storage technologies are introduced to align power generation with the building demand. This paper mainly focuses on hybrid photovoltaic-electrical energy storage systems for power generation and supply of buildings and comprehensively summarizes findings of authorized reports and academic research outputs from literatures. The global installation capacity of hybrid photovoltaic-electrical energy storage systems is firstly examined to show the significant progress in emerging markets. Particularly, the latest installation status of photovoltaic-battery energy storage in the leading markets is highlighted as the most popular hybrid photovoltaic-electrical energy storage technology for building applications. The research progress on photovoltaic integrated electrical energy storage technologies is categorized by mechanical, electrochemical and electric storage types, and then analyzed according to the technical, economic and environmental performances. Moreover, extensive research on hybrid photovoltaic-electrical energy storage systems is analyzed and discussed based on the adopted optimization criteria for improving future applications in buildings. It is indicated that the lithium-ion battery, supercapacitor and flywheel storage technologies show promising prospects in storing photovoltaic energy for power supply to buildings. Potential research topics on the performance analysis and optimization evaluation of hybrid photovoltaic-electrical energy storage systems in buildings are identified in aspects of the local adaption, flexible control, grid integration, as well as building resilience and intelligence. This study provides an insight of the current development, research scope and design optimization of hybrid photovoltaic-

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electrical energy storage systems for power supply to buildings and can serve as an explicit guide for further research in the related area.

Keywords

Electrical energy storage (EES); Solar photovoltaic (PV); Hybrid PV-EES systems; Optimization; Building power supply

1. Introduction

Recently, the scarcity of fossil fuels and its negative environment impact have attracted global efforts to cut down energy consumption and explore alternative energy resources. Given the fact that building sectors currently account for around 20-40% of total energy consumption in developed countries [1], renewable energy applications are promising substitutes for fossil fuels to mitigate energy crisis and environment pollution caused by building consumption. Among different renewable applications, solar and wind energy are showing remarkable growth in recent years [2]. Wind energy applications (i.e. wind turbines) are usually installed at a large scale [3] and extensively applied in remote and offshore regions [4]. For buildings with limited installation space, vibration control requirement and unfavourable wind environment in urban context, solar energy is more preferable as the power supply source and easier to be combined with existing structure. However, since solar energy is usually intermittent, unpredictable [5] and therefore not steadily consistent with building demand, corresponding energy storage technologies are necessary to obtain stable and reliable power supply. The integrated energy storage unit can not only adjust the solar power flow to fit the building demand and enhance the energy autonomy, but also regulate the frequency of utility grid for on-grid renewable energy systems [6]. Therefore, it is significant to investigate the integration of various electrical energy storage (EES) technologies with photovoltaic (PV) systems for effective power supply to buildings.

Some review papers relating to EES technologies have been published focusing on parametric analyses and application studies. For example, Lai et al. gave an overview of applicable battery energy storage (BES) technologies for PV systems, including the Redox flow battery, Sodium-sulphur battery, Nickel-cadmium battery, Lead-acid battery, and Lithium-ion battery [7]. A more detailed overview of PV-integrated BES technologies was conducted in [8], and the integration of PV-energy storage in smart buildings was discussed. Technical parameters of flywheel energy storage (FES), Lead-acid BES and Nickel-cadmium BES technologies were summarized and compared in [9]. The authors also reported that the performance of each EES technology varied with its ideal network application environment and application scale, so that thorough analyses should be conducted for technology selection. The system properties, current status and future utilization potential of both electrical and thermal energy storage technologies were examined in [10]. Working principles, technical properties and economic features were clearly summarized for mechanical, electrochemical and hydrogen energy storage technologies in [11]. Apart from reviewing the parametric analysis of EES technologies, pragmatic applications of the energy storage technologies were also examined. Typical applications of electrical energy storage technologies were summarized by Rohit and Rangnekar [12] as shown in Table 1.

Table 1. Typical applications of electrical energy storage technologies [12]

Applications	Bulk energy application		Ancillary services application					End-use energy application	
Technologies	Energy arbitrage	Peak shaving	Load following	Spining reserve	Voltage support	Black start	Frequency regulation	Power reliability	Power quality
PHES	Y	Y	N	N	N	Y	Y	N	N
FES	N	N	Y	Y	Y	N	N	Y	Y
CAES	Y	Y	Y	Y	N	Y	Y	Y	N
Lithium-ion BES	N	N	Y	N	Y	Y	Y	Y	Y
Lead-acid BES	N	N	Y	Y	Y	Y	Y	Y	Y
HES	Y	N	N	N	N	N	N	N	N
SCES	N	N	N	N	N	N	N	N	Y

Note: Y=Suitable application; N=Not suitable application; PHES = Pumped Hydro Energy Storage; CAES = Compressed Air Energy Storage; FES = Flywheel Energy Storage; BES = Battery Energy Storage; HES = Hydrogen Energy Storage; SCES = Supercapacitor Energy Storage

In terms of specific applications of EES technologies, viable EES technologies for power storage in buildings were summarized in terms of the application scale, reliability and site requirement [13]. An overview of development status and future prospect of large-scale EES technologies in India was conducted to identify technical characteristics and challenges of various systems [14]. The current status of EES technologies was elaborated according to battery and non-battery energy storage technologies. The utilization variability of various storage approaches was illustrated by a case study in US Pacific Northwest, and miscellaneous factors and methods of renewable energy management were covered in this study [15]. Attentions have also been paid to the application of energy storage technologies in microgrid. A comprehensive review study was conducted to investigate the operational and technical aspects of hybrid energy storage technologies for microgrid integration, and discussion has been focused on the system sizing, configurations and control methods of hybrid energy storage systems [16]. A more specific overview was conducted on control methods of energy storage systems for microgrid application, which was found to play a crucial part in the stability and economic aspects of microgrid [17]. To the best knowledge of authors, few review studies has been conducted to analyze the development of hybrid PV-EES systems for power supply to buildings.

Owing to increased government subsidies and reduced manufacturing costs of system components, a considerable progress on both the market application and technical investigation of hybrid PV-EES systems has been observed recently. Therefore, this study mainly focuses on the recent development of hybrid PV-EES systems for buildings including the global installation status as well as research progress on the performance analysis and system optimization. Section 2 reviews the global development of EES technologies for PV systems, specifying the installation status of the most commonly used PV-BES in buildings. Section 3 summarizes the technical, economic and environmental performances of major PV-coupled EES technologies categorized by mechanical, electrochemical and electric storage types. Section 4 examines hybrid PV-EES systems by different design optimization criteria for broader building application, and the widely applied optimization methods are compared and summarized. At last, potential future directions of applying hybrid PV-EES systems in buildings are identified in Section 5. The overall framework of this study is shown in Fig. 1. This study provides an insight of the current development, research scope and design optimization of hybrid PV-EES systems for power supply to buildings. Suitable hybrid PV-EES systems for building power supply and potential research gaps are clearly identified to promote future application of PV-EES technologies in buildings. Above all, this study can serve as an explicit guide for further research in the related area.

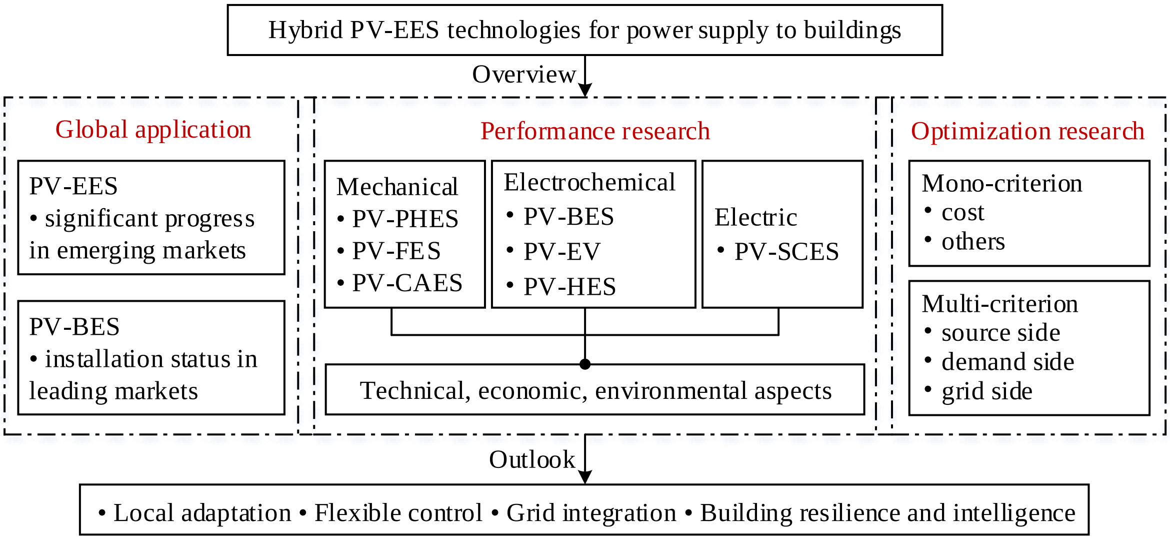


Fig. 1. Overall framework of the review on hybrid PV-EES technologies for power supply to buildings

2. Global development of electrical energy storage technologies for photovoltaic systems

The latest report of REN21 estimated that the global installation of stationary and on-grid EES in 2017 was up to 156.6 GW, among which PHES and BES ranked first and second with 153 GW and 2.3 GW respectively [2]. Encouraged by promising economic and environmental profits, the integrated solar PV and energy storage technology has been globally promoted in recent years. Germany increased the funding budget to facilitate the installation of small-scale PV paired energy storage systems [18], and an amount of US$ 370 million dollars was granted in 2017 for electric vehicle (EV) charging stations powered by renewable energy [19]. Czech Republic passed a new legislation that 5 kW energy storage capacity was necessary for 1 kW PV installation, and US$ 20.3 million was invested as government incentives [20]. An estimated 431 MWh energy storage (excluding pumped storage) was installed in 2017 in US, with up to 234 MWh in the first quarter [2]. California led the installation of the behind-the-meter storage in US, with about 110 MWh capacity accounting for 73% of total behind-the-meter installations in the whole country during 2017 [21]. New York was the first city in America to set the energy storage installation target of 100 MWh by 2020 [22]. And more ambitious plan was then established by Massachusetts to reach 200 MWh of energy storage capacity by 2020, with a grant of US$ 20 million for community storage projects [23]. China has experienced a leaping development of energy storage, which is motivated by the severe renewable energy curtailment and unbalanced national energy demand. More than 1.35 GW electrochemical energy storage was installed in China in 2017, increased by 9.6 times compared with the average growth from 2000 to 2015. China released its first national-level document in 2017 to implement energy storage, planning to achieve 2 GW electrochemical energy storage and 40 GW pumped storage by 2020 [24]. New markets on electrical energy storage are emerging in Italy and United Kingdom as important approaches to improve grid stability with the rising penetration of solar and wind energy [2]. South Korea plans on installing 100 MW battery energy storage as part of a 3 GW renewable hub on reclaimed land [25]. Electric vehicles (EVs) can serve as the demand and energy storage resources for supporting the flexible renewable energy systems applied in buildings. On the demand side, the EVs constitute part of the local electric demand in case they are locally charged in buildings, such as the home-charged EVs. On the storage side, they can act as mobile energy storage units to store surplus renewable energy and increase energy efficiency. Fig. 2 shows the distribution of countries which have established targets of the renewable electricity and electric vehicle. Large amounts of free charging stations for EVs are launched in Canada to reach the goal of eliminating fossil fuels and achieving 100% renewable energy [2].

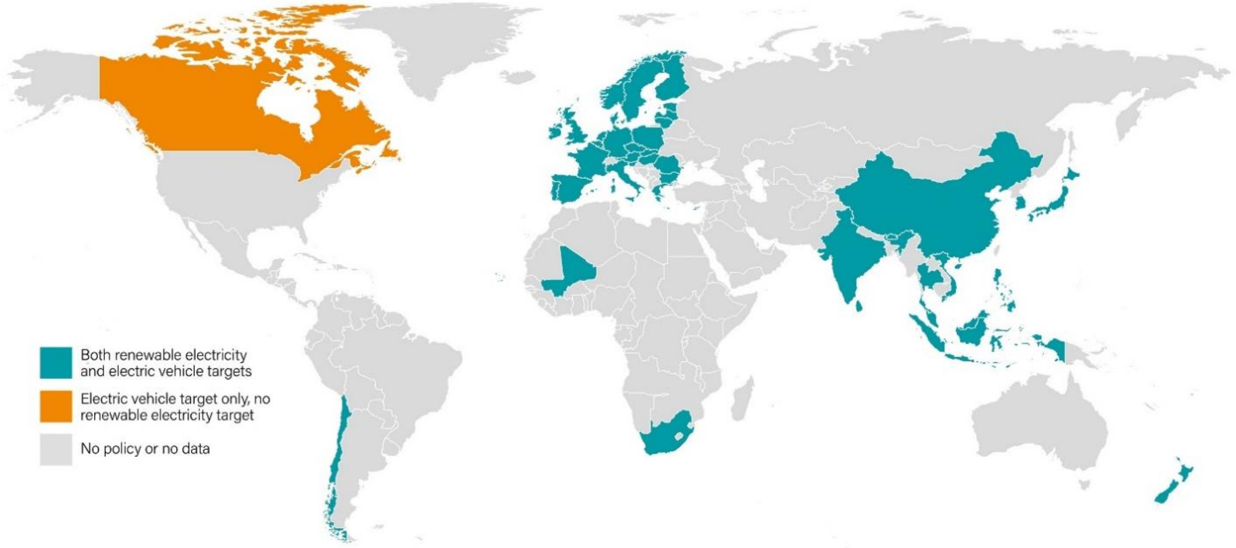


Fig. 2. National targets for renewable power and/or electric vehicles by the end of 2017 [2]

Although variable storage technologies have been identified in existing PV-EES studies, PV-BES still remains the most commonly used system for building power supply around the world. In view of the global development, a leading market has been observed in Australian households, with accumulated 28000 battery installations for solar PV storage by the end of 2017. Approximately 172000 PV systems were installed in Australian homes in 2017, with 12% of them using battery storages, up from the 5% use in 2016 [26]. Australia was proved to be the biggest residential energy storage market in the world in 2017 [21]. Most of these home batteries used lithium-ion materials, whose price declined from US$ 1000/kWh in 2010 to US$ 209/kWh in 2017, speeding up installations in recent years [27]. The payback time of PV-BES systems for typical Australian homes was estimated to be about 6-10 years depending on geographical locations [28]. A large amount of local government subsidy, US$ 25 million by the Andrews Government and US$ 150 million by the Weatherill Government, has been invested in 2017 to facilitate the establishment of PV-BES systems in Australia. Furthermore, a motivating feed-in-tariff scheme was launched by the Victorian Government to encourage households to feed their PV electricity into the utility grid in the peak load period [29]. In Germany, half of residential PV systems established in 2017 were paired with battery storage units, with about 80000 behind-the-meter installations by the end of the year [21]. About EUR 30 million was funded by the KfW to encourage on-grid PV-BES installations in Germany [30]. Sonnen, the first battery company providing lithium-ion battery for households, reported that the payback time of residential PV-BES systems can be decreased by 2-3 years if connected to the Sonnen community [31]. This company reached an agreement with the Italian government to install 20000 PV-BES systems in the next two years to establish a new virtual power plant in Italy [32]. In addition, about 25000 battery systems have been registered by April 2018 in Japan and an increasing trend can be anticipated in future [2].

The global EES installation during January to October in 2018 is summarized in Fig. 3. The US is leading the EES deployment during the first ten months in 2018, with a 937,093 kW capacity accounting for almost half of global installations. The capacity of lithium-ion BES is 170,612 kW taking up about 18.2% of EES installations in US during this period. Followed by Australia, around 569,500 kW EES installation is observed from January to October in 2018, sharing appropriately 30% of the total capacity around the world. Similar proportions of 5% and 6% can be seen in the UK and Canada for their EES installations in the first ten months of 2018.

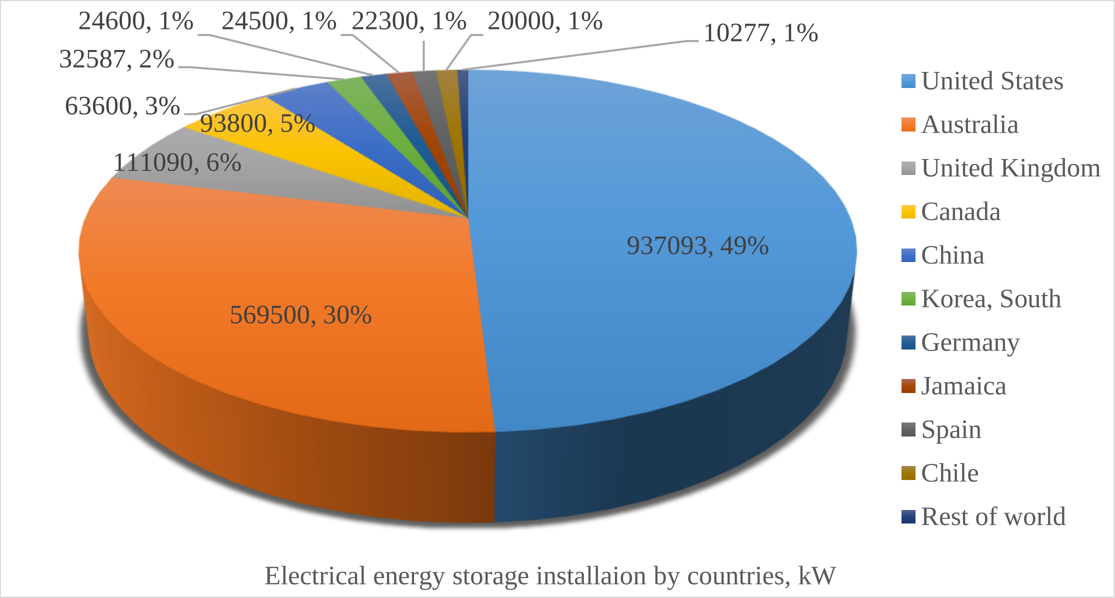


Fig. 3. Top 10 countries on electrical energy storage installation from Jan-Oct, 2018

[Data Source: DOE Global Energy Storage Database, US DOE, Office of Electricity Delivery and Energy Reliability]

3. Performance of hybrid photovoltaic-electrical energy storage systems for power supply to buildings

This section summarizes the recent research progress on widely used PV-EES technologies, which can be applied to the building power supply. Fig. 4 shows the review framework of the recent research progress on the system performance of hybrid PV-EES. These EES technologies can be sorted into three major categories including mechanical, electrochemical and electric storage according to their working mechanism [11]. The analyzed mechanical storage technologies include the pumped hydro energy storage (PHES), flywheel energy storage (FES), and compressed air energy storage (CAES). The discussed electrochemical storage technologies cover the battery energy storage (BES), electric vehicle (EV) energy storage and hydrogen energy storage (HES). And the electric storage technology in this study specifically refers to the supercapacitor energy storage (SCES). The system feature and working principle are introduced for each EES technique, and the recent research progress of these hybrid PV-EES systems is summarized from technical, economic and environmental aspects.

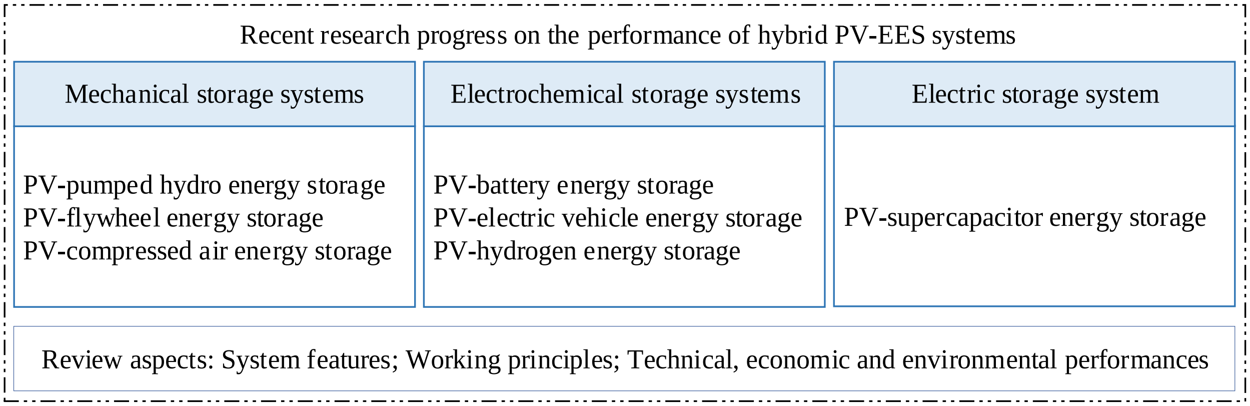


Fig. 4. Review framework of recent research progress on the performance of hybrid PV-EES systems

3.1. Mechanical storage technologies for photovoltaic systems

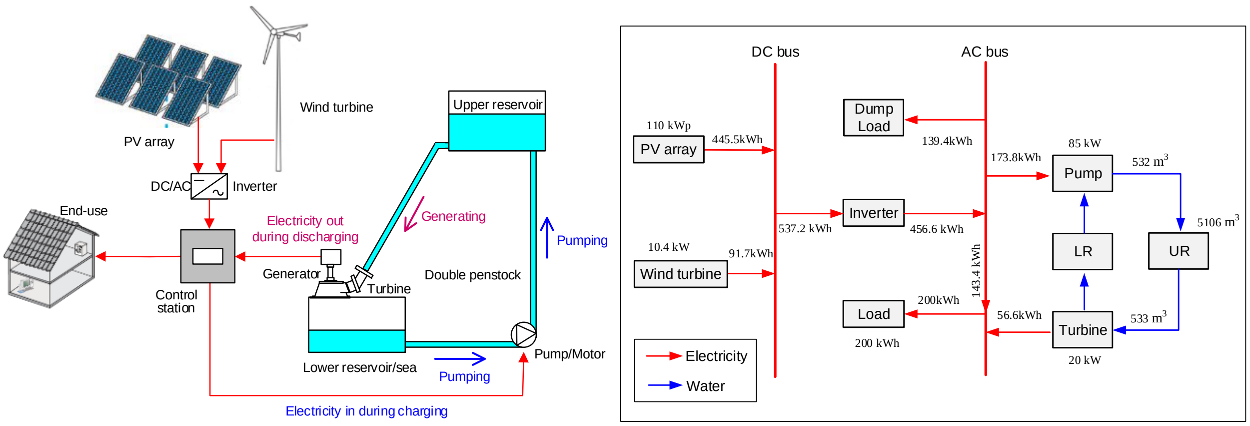
This section covers the recent research progress of three widely used mechanical storage technologies for PV systems, namely the PV-PHES system, PV-FES system and PV-CAES system. System features and working principles of each PV-EES technology are introduced, and their technical, economic and environmental performances are compared and summarized.

3.1.1. Hybrid photovoltaic-pumped hydro energy storage system

PHES (Pump Hydro Energy Storage) is the most mature and commonly used EES [33]. It is especially applicable to large scale energy systems [34], occupying up to 99% of the total energy storage capacity [35]. To further promote the penetration of renewable energy, PHES catches increasing attention as a promising integrated storage technology. Regarding the operation schematic of the hybrid PV-PHES system for power supply to buildings, the electricity generated by PV panels is used to pump water of PHES from a lower reservoir to a higher elevation during off-peak hours. And this part of stored potential energy can be released and transformed back to high-quality electricity to meet the peak power demand in buildings. As a widespread energy storage technology, PHES has many advantages when combined to PV generation systems: (1) high efficiency around 75% to 85% [10], (2) flexible and prompt response

[34], (3) stable and bulky power back up [36], (4) robust grid frequency support [37]. While, there are some inevitable challenges to further extensively exploit PHES plants, mainly concerning sites availability and long term effect on ecological environment [6].

With respect to the technical feasibility of hybrid PV-PHES system, both large-scale and small-scale applications have been explored. Margeta and Glasnovic developed a mathematical model to estimate the overall technological feasibility of a PV-PHES system applied in Europe. According to the result of sensitive analyses, crucial parameters including the total head, solar radiation, natural water inflow and hydro accumulation size, played a decisive role in determining the calculated power of PV unit [38]. The authors also presented an algorithm to find the relationship between PHES volume and PV power production to help select an optimal size for the PV-PHES system [39]. A case study applying the hybrid PV-PHES system in Croatia was conducted to verify the practicability of their proposed solution [40]. Ma et al. proposed a mathematical model to examine the technical feasibility of a standalone PV-wind system with PHES unit as shown in Fig. 5. With a further validation conducted in a remote island of Hong Kong, it is found that the PHES technology was a reliable and achievable tool to realize complete energy autonomy of renewable energy systems in remote regions [5]. In addition to large-volume PHES systems mentioned above, Javanbakht et al. evaluated the transient performance of a small-scale hybrid PV-PHES system concentrating on its control strategy. This study showed that controllers of grid-side converter and machine-side converter displayed satisfactory performance [41]. Chaudhary and Rizwan presented a smart on-grid energy management system connecting a PV-PHES system with demand response algorithm. Its performance was further investigated with MATLAB for a 5 kW PV system, showing that the established energy management system was quite flexible and reliable [42].



(a) (b)

Fig. 5. A hybrid PV-wind system with pumped storage system (a) schematic (b) daily power and water flow [5]

Apart from technical feasibility of hybrid PV-PHES, other important characteristics like economic and environmental performances also become focus of many studies. Ma et al. analyzed the economic performance of an off-grid hybrid PV-PHES system based on the lifecycle cost and levelized cost. The energy storage system with pumped hydro and hydraulic controller is proved superior to the battery energy storage in terms of economic benefit [6]. Li et al. assessed the technical and economic performances of a large-scale PV-PHES system according to the real data of an island in Japan. The storage dispatch role of PHES on the PV power system was examined and the simulation result showed that PHES can effectively contribute to a low levelized cost of energy (LCOE) for PV-PHES systems, especially in the circumstance of high PV penetration [43]. Aside from combining PHES to bulky renewable energy systems, using PHES in small-scale systems was explored based on LCOE but was found less economically competitive than large-scale installations by a case study in France [44]. Apichonnabutr and Tiwary proposed a mixed evaluation framework to study the tradeoff between economic and environmental performances of a standalone hybrid PV-wind-diesel system with micro pumped hydro and battery storage units. A case study was carried out on an existing micro pumped hydro power plant in Thailand, and the result indicated that the integration of micro PHES and the hybrid PV-wind-diesel system was preferred in ecologically sensitive areas [45].

3.1.2. Hybrid photovoltaic-flywheel energy storage system

FES (Flywheel Energy Storage) is one of oldest popular technologies [46] applied in power systems given its high power density [47], high energy efficiency for 93-95% [10], fast response and environmental sustainability [48]. When combining FES with an energy generation unit like PV, the flywheel absorbs excess energy generated by PV panels in a high-speed rotational disk to drive the shaft of the electric machine. When it turns to peak load hours, this part of stored kinetic energy can be converted into electricity and compensate for utility power supply [49]. Some objections are found to further facilitate its application including: large space required to install the mechanical system, additional cryogenic cooling devices [50], and high initial cost up to 1000-5000 $/kWh [11]. The typical storage capacity of FES is around 250 kW [10], which is relatively smaller compared with the other two mechanical storage technologies.

A small number of studies focus on the technical features of FES systems combined with renewable energy systems. Deeb et al. presented a distribution generation system with PV-FES in order to regulate the system voltage and improve energy efficiency. Both experimental and numerical methods were used to verify the developed control system [51]. Different techniques of FES are applied in an off-grid PV-wind system to achieve an effective control [52]. Tran et al. tested the FES system applied in a grid connected PV system by MATLAB, and the FES system was proved useful for smoothing the power flow of PV generators [53].

More attention has been paid to the economic and environmental impact of FES on hybrid PV-FES systems. Boukettaya and Krichen [54] developed a power management strategy for a grid tied PV-wind-FES system to simultaneously meet the dynamic residential load and reduce greenhouse gas emissions at a low cost. The supervising performance of the strategy was simulated by a nonlinear model and its feasibility was validated. Economic and environmental benefits of a hybrid PV-diesel-FES system were analyzed in [55] based on the platform of HOMER. Table 2 shows the net savings of the diesel consumption, CO_2 emission, total net present cost and cost of energy in the cases of without flywheel and with flywheel in the power system to verify the contribution of FES technology. Okou et al. designed flywheel rotor prototypes to promote power supply in sub-Saharan Africa based on locally available materials. A comparison of lifecycle cost of the proposed FES system and traditional lead battery storage system was carried out, showing the economic competitiveness of the FES. It was estimated to achieve about 37% per kWh of energy cost saving for solar home systems in rural areas [56]. Both technical and economic feasibility was investigated in [57] for a standalone PV-wind system coupled with a parallel connection of FES and BES in Greece. Nine scenarios with different energy storage technologies were compared through calculations and simulations, where FES systems were proved to have a better commercial prospect than electrochemical batteries.

Table 2. Comparison on net savings considering the flywheels in the power system [55]

Net savings	From DG to DG/FW	From PV/DG to PV/DG/FW	From PV/DG/Bat to PV/DG/Bat/FW
Diesel consumption (L/year)	484,872	23,668,500	22,765,956
CO_2 emissions (kg/year)	1,276,416	62,327,296	59,949,568
Total net present cost ($)	1,977,737,216	3,097,841,664	3,075,704,448
Cost of energy ($/kWh)	0.012	0.019	0.019

Note of simulation parameters: PV-2200 MW, FW (flywheel)-250 MW, DG (diesel generator)-2200 MW, and Bat (battery)-7426 kW.

3.1.3. Hybrid photovoltaic-compressed air energy storage system

CAES (Compressed Air Energy Storage) is another commercialized EES technology with bulk storage capacity alongside with PHES [58], although only two large-scale CAES plants are in operation all over the world [59].

Coupled with PV generators, spare energy from PV panels during low demand time is used to compress air into sealed underground caverns or large tanks for storage. And during peak period, the compressed air with high pressure is freed to drive the turbine and generate electricity. CAES is developed as a promising energy storage technology given its long duration and low capital cost around 2-100 $/kWh [10].

In terms of technical studies on the combined PV-CAES systems, much attention has been paid to the system efficiency. Cazzaniga et al. investigated the feasibility of combination of CAES and floating PV connected by steel cylinders, and the estimated storage system efficiency is over 80% [60]. A standalone small-size PV-CAES system was proposed to meet the load of a radio base station in [61], and a sensitive analysis was conducted to identify key operation parameters. The energy storage efficiency of the proposed small-scale CAES was estimated to be over 50%. Arabkoohsar et al. analyzed energy and exergy performance of a grid connected PV-CAES system with a peak capacity of 100 MW. A thermodynamic analysis of all components was conducted, while the annual operation performance in Brazil was predicted. The energy and exergy efficiency of the hybrid system was reported to be 17.9% and 16.2%, respectively [62]. Additionally, Zafirakis et al. developed a sizing algorithm for hybrid PV-CAES systems [63], and they studied a new dual-mode configuration of CAES to enhance the system energy autonomy with a case study of Aegean Sea. It is indicated that the proposed hybrid system can meet the night-time peak load for Greek mainland. A dynamic simulation model was also developed to estimate the performance of a grid tied PV-CAES system for a refurbished educational building in France, as shown in Fig. 6 [64].

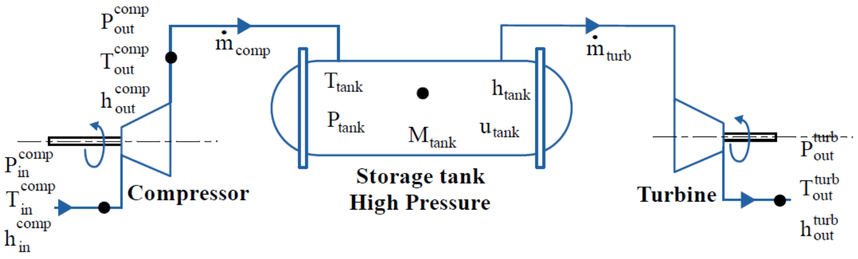


Fig. 6. The PV-CAES system for a refurbished educational building [64]

On the other side, few research focused on the economic and environmental aspects of PV-CAES. An integrated PV-CAES system was proposed in Brazil with a comprehensive consideration of the site selection, thermo-economic evaluation and power sale strategy [65]. It is estimated that the payback period of the on-grid hybrid PV-CAES plant is less than 9 years with a promising application potential. The authors then verified the feasibility of combining city gate stations to the PV-CAES system to enhance the system reliability and increase cost savings [66].

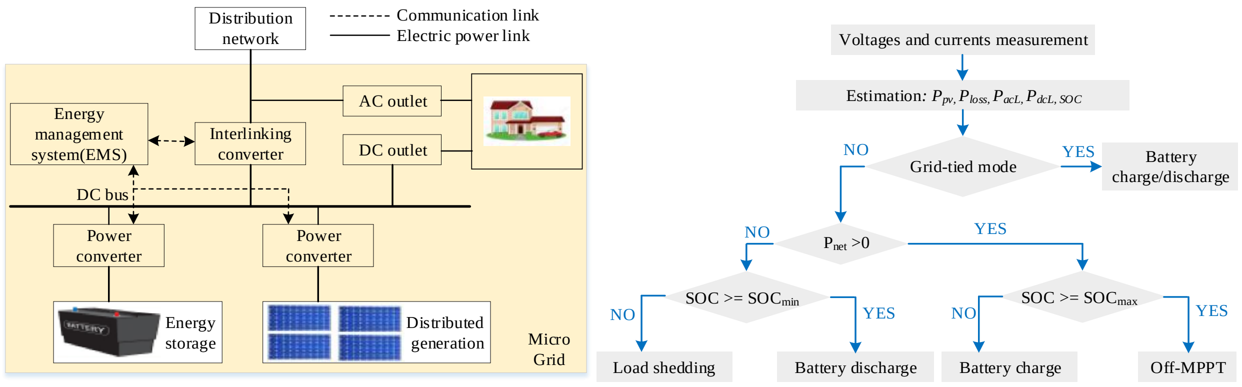
3.2. Electrochemical storage technologies for photovoltaic systems

This section includes three common electrochemical storage technologies for PV systems, namely the PV-BES system, PV-EV energy storage system, and PV-HES system.

3.2.1. Hybrid photovoltaic-battery energy storage system

With the descending cost of battery, BES (Battery Energy Storage) is developing in a high speed towards the commercial utilization in building [66]. Batteries store surplus power generation in the form of chemical energy driven by external voltage across the negative and positive electrodes. When supplying electricity to meet the demand in the discharging stage, electrons flow can be generated through electrochemical reactions [37]. BES is more popular with building occupants due to its fast response, high efficiency, and low demand for installation and maintenance [10].

A large amount of research has been conducted on the technical feasibility of hybrid PV-BES. In terms of system operation modes, two effective charging methodologies of a hybrid PV-BES system were developed to enhance the overall efficiency by dynamically modelling the PV panel and battery unit [67]. Weniger et al. studied the dynamic mismatch losses of on-grid PV-BES systems through simulation and experiment methods. It was reported that the battery component with a faster response led to higher savings for owners [68]. A fuzzy logic control algorithm was developed for a PV-BES system to prolong the battery lifetime and smooth the voltage [69], and a model predictive control strategy (shown in Fig. 7) was proposed for a microgrid integrated PV-BES system to stabilize voltage and ensure power balance [70].



(a) (b)

Fig. 7. A hybrid microgrid PV-battery system (a) structure (b) energy management system [70]

An effective sizing method of batteries for PV system was developed by a randomized algorithm, and the expected revenue of the PV-BES system was discussed considering the uncertainty of PV generation [71]. Klingler investigated the impact of EVs and heat pumps on the commercial market of hybrid PV-BES systems based on data collected from 415 households. It was found that both EVs and heat pumps contributed to higher profit for the self-consumption system [72]. In order to help households to adapt the on-grid PV-BES systems into off-grid systems, energy efficient air conditioning technique was also studied. This study indicated that building load adjustment with hot water and air conditioning can improve system economics even with reduced on-grid electricity costs [73]. However, there is still an argument that it is challenging for household PV-BES systems to be completely separated from the utility grid based on the analysis of residential customers in different locations of America [74].

Economic and environmental performances of PV-BES systems are increasingly addressed in recent research for evaluating their extensive applications. For example, Tervo et al. simulated the lifecycle performance and economics of the hybrid PV-BES system in 50 states of America. The impact of the PV size and battery capacity on the system performance and cost was examined. It is reported that the hybrid PV-BES system with appropriate sizing can be cost-competitive compared with the standalone PV system [75]. Schopfer et al. assessed the impact of electricity load profiles on the configuration and cost of the hybrid PV-BES system based on operation data from 4190 households. The result showed that small-size batteries can be more profitable based on predicting profitability of installing PV-BES systems with a machine learning algorithm [76]. The technical and economic performances of an on-grid PV-BES system were analyzed within Kyushu's market background. It was shown that the self-consumption rate varied with month and was higher in winter. In addition, the optimized residential PV-BES system sharing 2% grid load contributed to 1.1% peak shaving [77]. The PV-BES system was developed as an effective solution to domestic energy poverty in developing countries with a consideration of energy efficient appliances such as lamps and multi-cookers. It was simulated and optimized using iHOGA for several locations within the Earth's Sunbelt, where the cost of energy of the solar home system is found slightly cheaper than the traditional case in the short term, and notably cheaper in the longer term [78]. With respect to commercial application of PV-BES systems, the net present value (NPV) of PV-BES systems in Italy was assessed in [79], showing the economic viability of applying the hybrid PV-BES system to residential buildings in a mature market. The demand charging reduction of commercial PV-BES systems in Australia was evaluated by Park and Lappas [80], who found that the demand cost of hybrid PV-BES systems was lower than a local network. The effect of different types of tariffs on cost saving of the PV-BES system was examined in [81]. Moreover, the lifecycle environmental effect of household hybrid PV-BES systems in Turkey was evaluated and energy saving was predicted to be 4.7-8 times of current consumption in a lifecycle operation [82]. Lifecycle assessment on the CO_2 emission and cost saving of the PV-BES system was also conducted, based on the simulation of a building installed with 20 kW PV-BES system in the UK [83].

The most commonly used BES technologies for PV power supply to buildings are identified as the lithium-ion and lead-acid batteries as compared in Table 3. Lead-acid batteries have been used for energy storage in a commercial scale for several decades owing to its low cost and easy accessibility. While most home PV-BES systems coming onto the market prefer lithium-ion batteries for higher depth of discharge and less environmental footprint.

Table 3. Comparison of commonly used batteries for PV energy storage in buildings

Battery types	Lithium-ion batteries	Lead acid batteries
Life span (years)	lithium iron phosphate: 5-10 [84], lithium cobalt oxide: 5-7 [84], lithium manganese oxide: 10-30 [84]	3-15 [84], 5-15 [37]
Depth of discharge [84]	lithium iron phosphate: 50-90%, lithium cobalt oxide: 50%, lithium manganese oxide: 90%	50%
Cycle life (cycles)	lithium iron phosphate: 2000+ [85], lithium cobalt oxide: 500-1000 [85], lithium manganese oxide: 1000-1500 [85]	500-1000 [8], 200-1800 [86]
Round trip efficiency	lithium iron phosphate: 89% [84], lithium cobalt oxide: 97% [84], lithium manganese oxide: 75-95% [84]	70-90% [8], 65-80% [86]
Operating temperature [84]	lithium iron phosphate: 0 to 45°C, lithium cobalt oxide and lithium manganese oxide: -10 to 45°C	-10 to 45 °C
Investment cost ($/kWh)	1000-2000 [87]	300-600 [8], 150-500 [86]
Environmental impact [13]	very low	medium
Maintenance [13]	little	low
Recyclability [13]	medium	excellent
Advantages [87]	(compared with lead-acid batteries) longer cycle life and greater depth of discharge lighter weight and higher voltage smaller environmental footprint less maintenance demand	(compared with lithium-ion batteries) more mature technology relatively cheaper readily recyclable

Battery types	Lithium-ion batteries	Lead acid batteries
Disadvantages [87]	(compared with lead-acid batteries) higher cost less recyclability	(compared with lithium-ion batteries) limited depth of discharge require regular checks require external venting for operation

3.2.2. Hybrid photovoltaic-electric vehicle energy storage system

The EV (Electric Vehicle) is an emerging technology to realize energy storage for PV, which is promising to make considerable contribution to facilitating PV penetration and increasing energy efficiency given its mass production [88]. For PV powered buildings, the paired EV can serve from both energy demand and storage sides, which can help improve the on-site energy matching and regulate the peak load [89]. Four basic pathways to realize the storage potential of EV are reported as the smart charging, vehicle to grid, battery swap and repurposing retired batteries [90].

For technical features of PV-EV systems, energy management schemes are the main research focus. Sabillon et al. presented a dynamic scheduling method for residential PV-EV systems based on a rolling multi-period strategy. This approach can predict one-day-ahead operation information to appropriately deal with weather uncertainties and different charging behaviors [91]. A novel energy management scheme was developed for an on-grid PV-EV system, providing uninterrupted and steady-price charging. This scheme is reported to maintain 16.1% decline in charging price and achieve 93.7% grid burden relief [92]. The interaction between the PV-EV system and utility grid is also widely studied. The contribution of plug-in EV on balancing the fluctuation of an on-grid PV-wind system was evaluated in [93]. Three control models separately supervising the mobility behavior, vehicle charging cost and electricity price were utilized for load management. It is found that the contribution of EV is determined by the renewable energy generation profile, while the additional utilization of negative residual load was 34-52% under the studied scenario of German 2030. The grid reliability under stochastic behavior of the plug-in EV and renewable energy system was estimated in [94]. A new method to manage grid power was developed to meet the plug-in EV, leading to a stabilized system. Drude et al. introduced the peak demand market of on-grid PV-EV systems in urban regions of Brazil [95]. The co-benefits of large scale PV-EV systems were also identified in [96], mainly covering the reduction in EV capacity increase and PV curtailment.

The system performance like energy efficiency of PV-EV systems can be greatly affected by user charging behaviors as pointed out by some existing studies. The influence of consumer behaviors on the energy transition of grid connected PV-EV systems was investigated based on the historical data of 40 regions in Netherlands. Great difference in spatial diffusion patterns among regions was observed in the study, indicating that grid tied PV-EV systems are only suitable for further promotion in certain areas [97]. A real-time system showing prioritization and cryptocurrency was proposed to encourage EV users to charge in a renewable energy friendly schedule. Both simulations and experiments were conducted to validate the system performance, showing an increased penetration of solar energy in the tested campus of Los Angeles [98].

Regarding economic and environmental aspects of PV-EV systems, the technical and economic feasibility of on-grid PV assisted EV charging system was analyzed using HOMER for existing petrol stations in Malaysia. It is found that these stations can meet 2.14% initial EV penetration and the payback time for system installations is about 6.3 years [99]. Coffman et al. compared the lifecycle cost and greenhouse gas emissions of PV integrated EV and other cars in Hawaii. It is shown that the PV charged EV is $1200 less expensive than other cars in terms of lifecycle expenditure, but it is still a costly strategy for reducing greenhouse gas emissions [100]. Roselli and Sasso investigated the energy and environmental performances of the PV-EV system in an office building of Italy as shown in Fig. 8. Considering the daily driving distance of EV, it is indicated that 40% energy saving and CO_2 emission reduction can be reached compared with traditional operation system [101]. The cost effectiveness and environmental contribution of PV-EV systems are also clarified for meeting large energy storage requirement and mitigating greenhouse gas emissions [102].

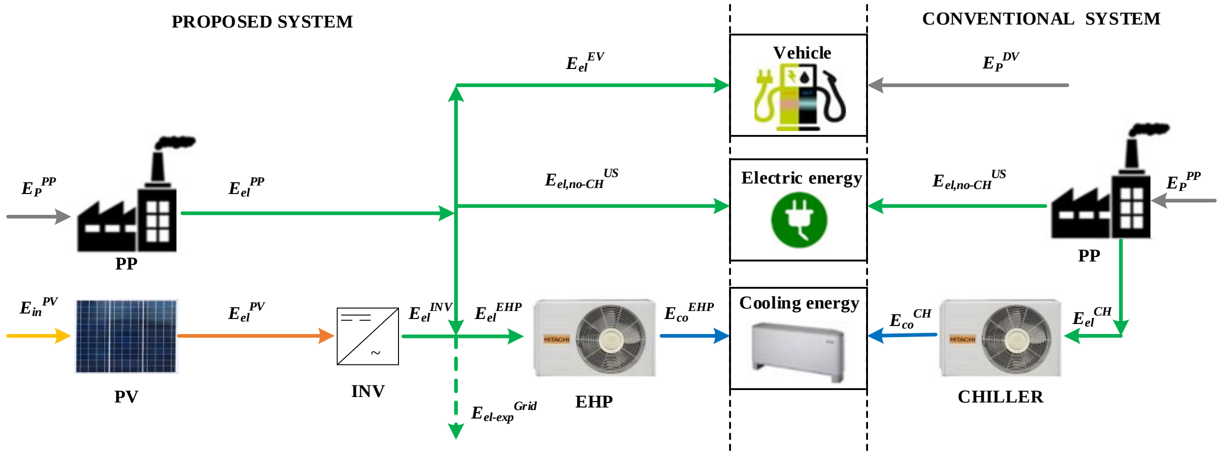


Fig. 8. Configuration of the proposed and conventional PV-EV system for an office building [101]

3.2.3. Hybrid photovoltaic-hydrogen energy storage system

HES (Hydrogen Energy Storage) is one of important energy storage technologies as it is almost completely environment-friendly and applicable to many economic sectors besides EES [103]. It is a promising candidate leading to a low carbon hydrogen economy [104]. Hydrogen is the lightest chemical element with the highest specific energy that can be easily stored and transported for long distance [105]. In a joint PV-HES system, surplus electricity from PV panels is used to produce hydrogen via electrolysis and then stored it in underground caverns or steel containers during off-peak time. And the stored hydrogen can be the fuel for power production in peak demand time through an internal combustion engine or fuel cell [106]. The initial costs of electrolyzer and fuel cell are 1500 $/kW and 2000 $/kW respectively [107], while the total system capital cost is 10-20 $/kWh with a typical storage capacity of 0-50 MW for HES [10].

With respect to the technical performance of the PV-HES technology, Tebibel and Medjebour compared the performance of PV-assisted hydrogen generation using water, methanol and electrolyzers. A case study was then conducted in Algiers city showing that the electrolysis supported by sulfur has the highest performance in hydrogen production [108]. An energy management scheme for an off-grid PV-HES system was also developed in their study to obtain high overall efficiency and safe working condition [109]. A comprehensive control and energy management algorithm was established for a microgrid PV-wind-HES system to obtain high-quality and stable performance under the condition of demand variations and random renewable energy resources [110]. A model predictive control was used to estimate the reliability and energy loss of newly installed PV-HES systems in two islands of Reunion Island and France, which previously used diesel generators power supply. The studied showed 76% decline in system default time and 11% energy loss [111]. The annual energy generation of a hybrid PV-wind-HES system in Chicago was predicted to meet a varying load with a mean of 1 kW based on the Hybrid2 simulation software. It was shown that the annual energy production of the hybrid system exceeded the load by 160% and the hybrid system achieved consistent energy autonomy using a very small battery bank [112]. For more technical studies based on practical data, the performance of a PV-HES system in Antarctica was analyzed with two-year operation data. It is found that the proposed HES system can offer more than 40% of total energy for a local house, leading to an annual saving of at least 450 L fossil fuel [113]. A novel methodology to determine the efficiency of a HES system coupled with renewable energy resources was developed as shown in Fig. 9. And the positive effect of the HES system on the electricity system and utility grid was clarified in this research [114]. A hybrid PV-wind system was developed for a zero-energy building equipped with a hydrogen vehicle, and simulation results based on TRNSYS shown that the hydrogen vehicle made significant contribution to improving the energy efficiency of renewable systems [115].

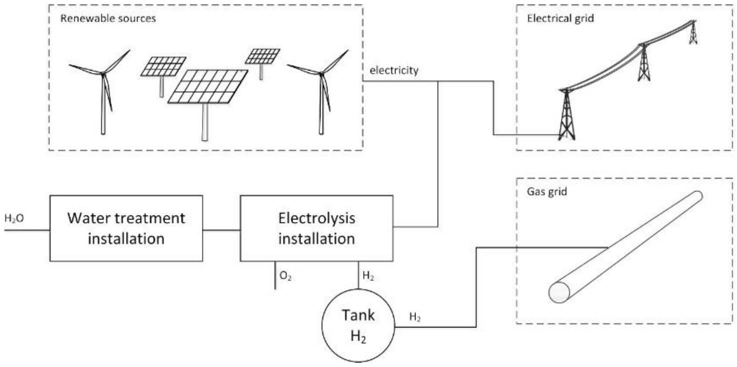


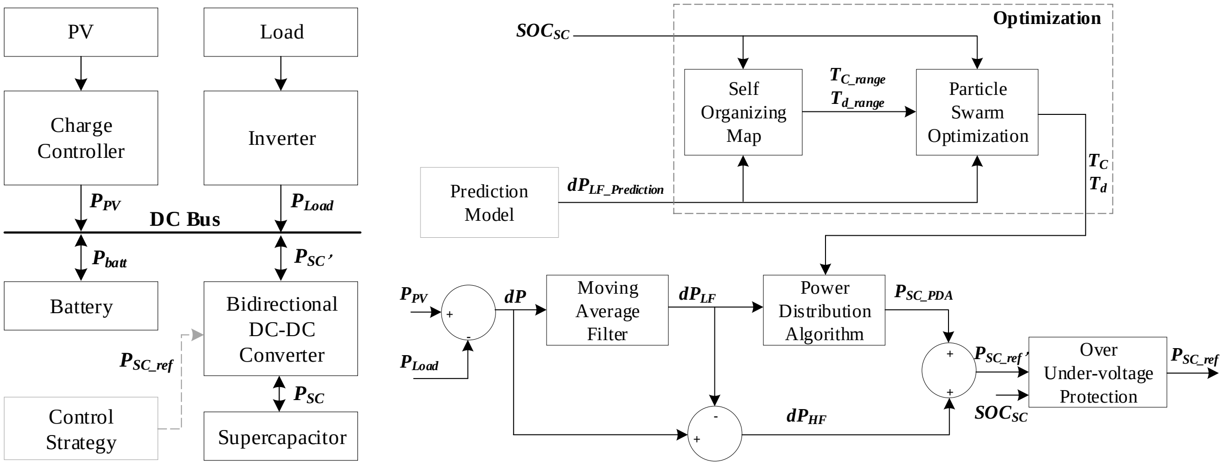
Fig. 9. Hybrid renewable system with hydrogen storage [114]

Turning to the economic and environmental studies on hybrid PV-HES systems, Pu et al. established an energy management control scheme for a PV-HES system, and verified its cost effectiveness and stability by a 72 h online test in a RT-LAB semi-physical system [116]. The energy, exergy and economic analysis of an off-grid hybrid PV-wind-HES system was performed in [117], in which PV, wind and HES components account for 20%, 28% and 50% of the total investment and the payback period of the hybrid system is about 11 years. The HES system was developed as an technically and economically effective way to solve problems of renewable energy curtailment and chemical pollution in Xinjiang, China [118]. The techno-economic feasibility of applying the renewable energy system integrated with hydrogen vehicles was studied to reduce the cost and emission of buildings [119]. The thermo-economic operation of a zero-emission autonomous PV-HES system was analyzed via a detailed cost model. The unit electricity cost of the proposed system for the demand of 100 households was around 0.216 EUR/kWh, and could be further lowered with long lifetime of HES unit [120].

3.3. Electric storage technology for photovoltaic systems

The electric storage technology for PV system in this review means the hybrid PV-SCES (Supercapacitor Energy Storage) system. Supercapacitor, also called electrochemical capacitor, electrolytic capacitor or ultra-capacitor, usually has a capacity of several thousand Farads and can offer a current of hundreds of Amperes to transfer a large amount of energy during a short period. The most common type of supercapacitor is electric double-layer capacitor, who stores energy between the double layers through the phase interface of electrodes and electrolytes motivated by electrostatic interaction. The vital parameters for SCES to accumulate enormous power are the layer thickness and large electrodes surface [121]. SCES can act as the complementary technology for other EES technologies given its fast charging time, high energy efficiency of 90-95%, large storage capacity around 300 kW, and long lifetime over 20 years [10]. The capital cost of the current SCES is around 2000 $/kWh, comparable to lithium batteries [10].

For the technical aspect of PV-SCES systems, a theoretical study on the energy conversion and storage efficiency of PV-SCES technology with a semi-analytical model was published by Lechene et al. [122]. Active materials to improve the system efficiency were summarized in [123], and a novel sulfide thin film was also introduced for the application of PV-SCES systems [124]. Much attention has been paid to hybrid battery and supercapacitor technologies when served for PV energy storage, since these two EES technologies can complement each other. An adaptive control method was proposed for an off-grid PV-battery-supercapacitor system to achieve superior flexibility, as presented in Fig. 10. The supercapacitor utilization was improved by 7.33 times with the proposed method [125]. More controllers for PV integrated SCES systems were established, in which a two-layer power flow control for a PV-battery-supercapacitor system was presented to manage uncertainties and variations of solar resources and determine the optimal energy delivery [126]. Yin et al. proposed a experimentally validated method for a PV-diesel-supercapacitor system to maintain the power balance and improve system stability [127]. In addition, a novel simulation model was developed to realize the harmonic transient simulation for a standalone PV-battery-supercapacitor system. Corresponding case studies validated the higher accuracy and lower computational burden of the proposed model compared with conventional extended harmonic domain based models [128].



(a) (b)

Fig. 10. Standalone PV system with battery-supercapacitor storage (a) configuration (b) control strategy [125]

On the contrary, few literatures focused on the economic performance of PV-SCES. Jing et al. studied the technical and economic viability of standalone PV systems with both battery and supercapacitor storage technologies. The simulation work based on profiles of a rural area in Sarawak showed that hybrid energy storage systems can contribute to an improved battery cycle life and reduced overall operation cost [129].

3.4. Discussion on performance of hybrid photovoltaic-electrical energy storage systems

Table 4 compares the characteristics of electrical energy storage technologies covering technical, economic, environmental indicators, major advantages and disadvantages. It is shown that PHES and CAES technologies have larger storage capacity, longer life time and relatively lower capital cost than other EES technologies. The storage capacity of FES and lithium-ion BES technologies is smaller while their capital cost is higher. SCES and FES technologies have superior energy efficiency with fastest response time. The HES technology has lowest energy storage efficiency but its capital cost is the most favorable. The lifetime of mechanical and electric storage technologies is generally longer than electrochemical storage technologies. The environmental impact of FES and lithium-ion BES technologies is the lowest.

Table 4. Comparison of characteristics of electrical energy storage technologies

EES technology	Capacity [10] (MW)	Efficiency [10] (%)	Capital cost [10] ($/kWh)	Life time [10] (years)	Life time (cycles)	Response time [10]	Environmental impact [13]	Advantages [15]	Disadvantages [15]
PHES	100-5000	75-85	5-100	40-60	10000-30000 [130]	fast (ms)	high	mature technology high energy capacity high power capacity flexible response low cost and long life	site limitation high environmental impact long construction time
FES	0.25	93-95	1000-5000 [11]	20+ [11]	20000+ [37]	very fast	no	high power density fast response low environmental impact	low energy density high initial cost space requirement high standing losses [9]
CAES	3-400	50-89	2-100	20-60	8000-12000 [130]	fast	high	mature technology long duration	site limitation need gas fuel input long construction time

EES technology	Capacity [10] (MW)	Efficiency [10] (%)	Capital cost [10] ($/kWh)	Life time [10] (years)	Life time (cycles)	Response time [10]	Environmental impact [13]	Advantages [15]	Disadvantages [15]
								low capital cost low environmental impact	
Lithium-ion BES	0.1	75-97 [84]	1000-2000 [87]	5-30 [84] 5-15 [37]	1500+[15], 1000-10000 [86]	fast	very low	long cycle life high efficiency high depth of discharge [87] light weight [87]	higher initial cost less recyclability [87]
Lead-acid BES	0-40	70-90 [8], 65-80 [86]	300-600 [8], 150-500 [86]	3-15 [84] 5-15 [37]	500-1000 [8], 200-1800 [86]	fast	medium	mature technology relatively cheap readily recyclable [87]	limited depth of discharge require regular checks [87] require external venting
HES	0-50	20-50	10-20	5-15	1000+ [37]	good (<1s)	low	high energy density	high initial cost low efficiency
SCES	0.3	90-95	2000	20+	100000+ [11]	very fast	low	high power density long cycle life high efficiency quick recharge	short term power high initial cost low energy density

In terms of application in storing PV energy for power supply to buildings, lithium-ion BES, SCES and FES technologies show great potentials with the applicable storage capacity, fast response, relatively high efficiency and low environmental impact. However, further efforts should be made to lower their capital and operation cost for wider applications in buildings. More research should be conducted to improve materials and configurations of these promising PV-EES technologies for cost competitiveness. Besides, it is significant to investigate the operation combination (e.g. considering the dynamic building load and various building functions) of these applicable PV-EES technologies with buildings for higher overall energy efficiency.

Table 5 summarizes and compares the major research focus on the performance of hybrid PV-EES systems in terms of technical, economic, and environmental aspects. It is indicated that the technical performance of hybrid PV-EES systems has been widely analyzed covering the system configuration, system efficiency, energy management, grid integration and consumer behavior. Increasing attention is paid to the economic performance of hybrid PV-EES systems considering the popular economic indicators such as the lifecycle cost, LCOE, NPV, payback period and financial saving. However, few research investigates the environmental performance of hybrid PV-EES systems, despite that some topics related to the environmental cost, greenhouse gas emission and chemical pollution have been preliminarily studied.

Table 5. Major recent research focus on the performance of hybrid PV-EES systems

Hybrid systems	Technical aspects	Economic aspects	Environmental aspects
PV-PHES	mathematical model [5, 38] size determination [39, 40] energy management [41, 42]	lifecycle cost [6] levelized cost [6, 43, 44] net present cost [45]	environmental cost [45]
PV-FES	energy management [51, 52] grid integration [53]	levelized cost of electricity [55, 57] net present cost [55, 57] lifecycle cost [56]	greenhouse gas emission [54, 55] fuel consumption reduction [55]
PV-CAES	energy efficiency [60-62] exergy efficiency [62] sizing determination [63] energy management [64]	payback period [65] net present value [66]	
PV-BES	energy efficiency [67, 72] grid integration [68, 73, 74] energy management [69, 70] sizing determination [71]	lifecycle cost [75] net present cost [76, 77, 79] levelized cost of electricity [78] financial saving [80, 81]	lifecycle environmental effect [82] lifecycle CO_2 emission [83]
PV-EVES	energy management [91, 92] grid integration [93-95] system benefit [96] consumer behavior [97, 98]	payback period [99] financial saving [101]	CO_2 emission [101] greenhouse gas emission [102]
PV-HES	component analysis [108] energy management [109-111] energy efficiency [112-115]	cost effectiveness [116] lifecycle cost and payback period [117] unit cost of electricity [120]	chemical pollution [118]
PV-SCES	energy efficiency [122-124] energy management [125-128]	operating cost [129]	

Based on the above comparative analysis and discussion of existing performance studies of PV-EES for power supply to buildings. Research gaps are identified in the following aspects:

(1) Hybrid PV-EES technologies aimed at building power supply have specific requirements on the application conditions such as the geography, weather, storage scale and building load. It is suggested to comprehensively consider

local conditions from the source side, demand side and grid side when investigating the technical, economic and environmental feasibilities.

(2) Control strategies supervising the power distribution among all components including the PV panel, EES unit, building and utility grid should be further studied to achieve reliable, efficient, flexible and smart building management. Theoretical control algorithms should be established and validated to address the synergistic operation of these major components.

(3) Interaction between hybrid PV-EES systems and utility grid needs further in-depth investigations. Comprehensive and reliable grid integration indicators should be developed for pragmatic application scenarios. Both the single building and building cluster should be studied to assess the impact of PV-EES systems on the utility grid. The application of on-grid PV-EES systems for building power supply will facilitate an enlarged penetration of PV into urban areas and mitigate the peak demand on the utility grid. Economic analyses on grid tied PV-EES systems should also be carried out to guide policy makers to develop more effective incentive strategies to encourage the commercialization of PV-EES technologies.

4. Optimization of hybrid photovoltaic-electrical energy storage systems for power supply to buildings

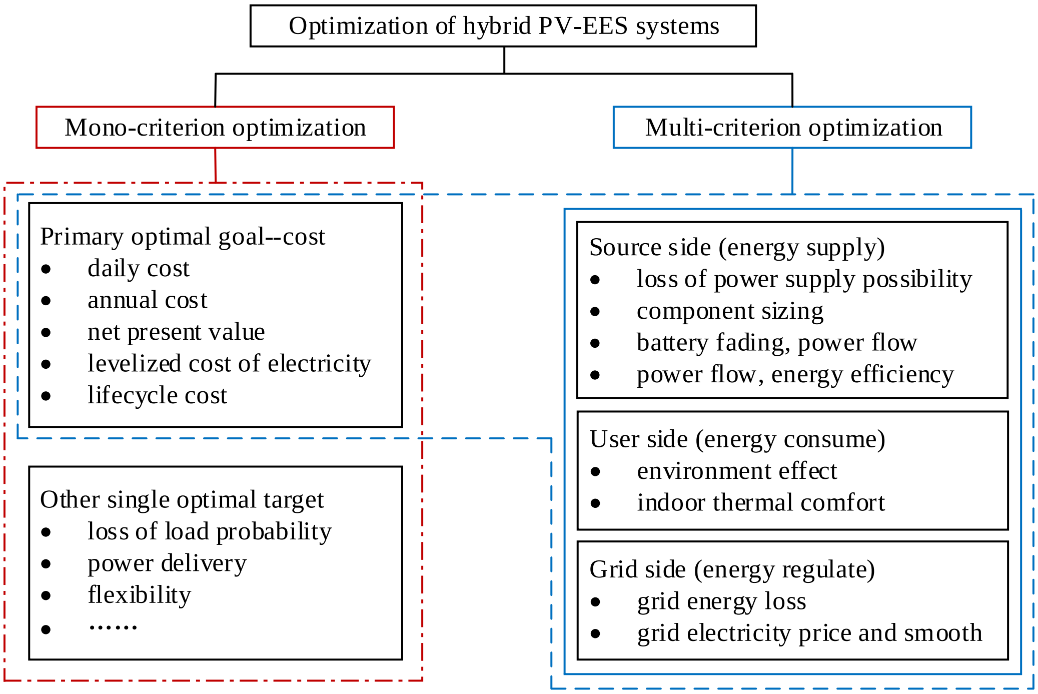


Fig. 11. Optimization criterion of hybrid PV-EES systems

Optimization of hybrid PV-EES systems has been extensively investigated to improve the system performance and practical application in buildings. The concerns of major stakeholders from the source side, demand side, and grid side have been addressed by existing studies. This section summarizes these studies based on applied optimization criteria shown in Fig. 11, in which different optimization methods are also identified and explained.

4.1. Mono-criterion optimization of hybrid photovoltaic-electrical energy storage systems

Cost is a primary indicator of the system utilization and is therefore identified as a popular optimization criterion. Different kinds of cost including the daily cost, annual cost, total NPV, LCOE, and lifecycle cost can be the single criterion in optimizations. For example, the daily operation cost composed of the energy cost and battery degradation cost was taken as the optimization criterion for a grid connected PV-BES system [131]:

$$Objective\ function = \sum_{k=1}^{N} C(k) - BDC_{cyl}(k) - BDC_{calAg}(k) \tag{1}$$

where $C(k)$ is the billed cost for the k^{th} time interval; BDC_{cyl} is the battery degradation cost caused by cycling; and BDC_{calAg} is battery degradation cost caused by calendrical ageing. Dynamic programming was used to solve this non-linear constrained optimization problem. And it is indicated that charging battery from PV systems contributed to the grid load balance.

The minimum daily operation cost of hybrid PV-EES system is also targeted by other methods. The genetic algorithm (GA) and the Particle Swarm Optimization (PSO) algorithm, were applied to control the battery charge and discharge rates in a PV-wind-BES system. The daily operation cost of the hybrid system was reported to be reduced by 31% with GA and 28% with PSO compared to a baseline without battery storage [132]. Anna et al. also clarified the effectiveness of PSO in obtaining the minimum daily cost for the PV-PHES system [133]. A robust optimization model was proposed to examine the performance of a PV system with thermal and battery storage techniques. The study achieved a daily cost reduction of 5.7% and a standard deviation decrease of 36.4% by experiments [134]. The weekly and daily operation cost of an on-grid hybrid PV-wind-BES system was taken as the optimization criterion of a fuzzy logic controller based on the Shuffled Frog Leap (SFL) algorithm. Using the time-varying prediction of the grid electricity price and environment parameters, the fuzzy logic controller achieved less fluctuation and a higher state of charge for the battery stack [135]. An efficient Harmony Search (HS) algorithm was proposed to optimize the charge schedule of the battery storage unit in a PV-BES system. Based on realistic residential loads and generation data, the electricity bills of consumers were further reduced by the proposed algorithm compared to the optimization result with GA [136].

A growing number of literatures have investigated the optimal PV-EES systems for the minimum annual cost, because it offers a more comprehensive bill reference for users. A capital recovery factor (CRF) was employed to transform the initial capital cost into the annual capital cost, defined as Eq. (2) [137]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

where i is the interest rate of the hybrid system; and n is the life span of the hybrid system. An evolutionary-PSO algorithm was proposed to optimize the total annual cost of a hybrid PV-wind-EES system including the initial cost as well as operation and maintenance cost. The simulation results validated the superiority of the evolutionary-PSO algorithm in terms of the convergence and simulation time compared with PSO, HS, differential evolution (DE) and GA [138]. Based on the calculated system annual energy cost, an energy management system was developed to minimize the cost of energy from the utility grid and maximize the profit from the hybrid PV-wind-EV system. It is validated that the proposed energy management model can be utilized to evaluate retired EV batteries in residential applications and microgrid control strategies [139]. For a standalone microgrid PV-BES system, the parallel algorithm was used to achieve the minimum annual operation cost. The material of PV panels and batteries was also analyzed for a cost optimization. It was reported that decreasing the demand of battery materials was the main approach to reduce the system operation cost [140].

Based on the total annual cost, the NPV is further proposed as an optimization criterion for hybrid PV-EES systems. Total NPV of an off-grid hybrid PV-HES system was minimized by the Flower Pollination (FP) algorithm. NPV of four main components, namely the PV unit, fuel cell, electrolyzer and H_2 storage tank, can be formulated as Eq. (3) [141]:

$$\mathrm{C} = C_I + C_R + C_{O\&M} - \mathrm{S} \tag{3}$$

where C_I is the initial cost of system components; C_R is the replacement cost of system components; $C_{O\&M}$ is the operation and maintenance cost of system components; and S is the salvage value of system components. The proposed FP optimization algorithm was proved to be more efficient and robust than the Artificial Bee Colony (ABC) and PSO. The FP algorithm was also utilized to explore the minimum total NPV for a hybrid PV-wind-HES system [142]. The HS algorithm was utilized to minimize NPV of an on-grid PV system with and without battery storage units. The simulation results showed the promising prospect of installing PV systems in Iran under the anticipation of increased utility electricity prices [143]. Various optimization techniques including FP, HS, ABC and the firefly algorithm (FA), were used to minimize NPV of a hybrid PV-biomass-BES system, where the loss of power supply probability (LPSP) and percentage of the excess energy were specified. This study found that FA was the most efficient approach to achieve the optimal solution, while ABC needed the maximum execution time [144].

Combining NPV and the building demand, LCOE, as the optimization criterion of hybrid PV-EES systems, is proposed to evaluate the performance of the PV-battery system as per Eq. (4) [145]:

$$LCOE = \frac{NPV_{sum} \cdot \frac{(1+i)^{t_{ref}} \cdot i}{(1+i)^{t_{ref}}-1}}{E_{load}} \tag{4}$$

where NPV_{sum} is the total NPV of system components; t_{ref} is the reference time frame for the cost calculation; i is the interest rate; and E_{load} is the annual load demand of the building. This study developed a modular simulation model to solve the optimization problem with GA based on the MATLAB platform, and examined the superiority of the method with a comparative analysis. LCOE of an off-grid renewable energy system was optimized by the enumerative method and compared with a real PV-BES system in Spain. The result showed that the optimized case contributed to a 9.7% decrease in LCOE and a 48.5% decrease in the battery service period [146].

Considering anticipated costs of system elements such as the PV array and battery tank, the lifecycle cost of PV-EES systems can be another optimization target. The lifecycle cost of a hybrid renewable energy system contains the capital cost (CC), operation and maintenance cost (MC), as well as replacement cost (RC) of all components. The objective function can be formulated as Eq. (5) [147]:

$$Objective\ function = Min \sum_{m=PV,WT,FC,Ele,H2,BAT,Inv} (CC + MC + RC)_m \tag{5}$$

It is pointed out that the HS algorithm has a good exploitation performance but may lead to a premature convergence. Therefore, a hybrid algorithm combining the annealing algorithm, HS, and chaos search algorithm was proposed to achieve a better solution. Considering the lifecycle cost, the hybrid PV-wind-BES system was found to be more cost-effective and reliable than the hybrid PV-wind-hydrogen system. The Renewable Energy Optimization model was applied to optimize the lifecycle cost of a “solar plus” system with PV, energy storage and load control units. The solar plus system was proved more cost-effective in some challenging electricity rate structures [148]. A hybrid PV-fuel cell system with battery storage was sized and optimized for an Indian village via the HOMER platform to achieve minimal lifecycle cost [149]. The overall cost consisting of the device cost, fuel cost and penalty of constraint violations was utilized as the optimization target of a hybrid system with tri-generation units and multistorage technologies. The PSO-based model was applied to size all components and operation strategies [150]. If the technical and environmental benefit of using renewable energy systems is taken into consideration, the cost function of a PV-BES system can be defined as Eq. (6) [151]:

$$CF = \sum_{n=1}^{N}\left([(B_{ARB} + B_{ENV} + B_{LOSS}) \times 365 + B_{TRANS} \times 12 - C_{M\&O}] - \left(\frac{1+ir}{1+dr}\right)^{n}\right) - C_{CA} \qquad (6)$$

where B_{ARB}, B_{ENV}, B_{LOSS}, B_{TRANS} are the energy price arbitrage benefit, environmental emission reduction profit, energy loss profit, and transmission access fee profit, respectively; $C_{M\&O}$ and C_{CA} are the annual maintenance cost and capital cost; ir and dr are the inflation and discount rate; N is the life span of system; n is the calculated year. The optimization problem was solved by GA with the liner programming method performed on DIgSILENT and MATLAB.

Apart from the cost, other factors such as the loss of load probability, power delivery and flexibility have also been taken as the single criterion for hybrid PV-EES optimizations. For instance, the loss of load probability of an off-grid PV-BES system was optimized for the household, school and health center in typical rural areas. The study also confirmed the necessity of conducting the reliability assessment of standalone hybrid PV-wind-EES systems [152]. A chance-constrained stochastic optimization was conducted to develop the day-ahead planning algorithm and real-time operation algorithm for the energy management of a grid tied PV-BES system. The simulation result showed the effectiveness of these two algorithms in maximizing the power delivery [153]. A new optimized control algorithm was adopted to investigate the flexibility of a PV-EES system. Five schemes with different incentive options were studied to test the developed control algorithm. This study indicated that the algorithm can be adapted for different options and the storage unit plays a major role in the flexibility performance [154].

4.2. Multi-criterion optimization of hybrid photovoltaic-electrical energy storage systems

On top of minimizing the cost of PV-EES systems, multi-criterion optimization studies are conducted to consider additional objectives from three main structural modules of PV-EES systems: source side (energy supply), demand side (energy consume) and grid side (energy regulate).

On the source side, a considerable amount of research focuses on exploring the system reliability and stability. Multi-objective PSO was applied to simultaneously maximize the system reliability and minimize the total present cost. Three different combinations, namely PV-wind-BES, PV-BES, wind-BES, were compared by modelling analyses with HOMER, where PV-wind-BES was determined to be the best combination in terms of the system reliability and cost [155]. In another study on a standalone hybrid PV-wind-PHES system, LPSP and the lifecycle cost were optimized by GA. A comparative analysis was also conducted on other renewable energy systems including the PV-PHES system and wind-PHES system, in which the combination of PV and wind performed best both economically and technically [156]. The Multi-Objective Self-Adaptive Differential Evolution (MOSaDE) algorithm was used to optimize the size of a PV-wind-diesel system with battery storage to minimize the cost of electricity and LPSP. The study derived optimal solution sets for three real cases [157]. The Non-dominated sorting Genetic Algorithm-II (NSGA-II) was adopted to find the optimum investment cost and exergy efficiency for a hybrid PV-CAES system [158]. An improved method of the electrical system cascade analysis based on MATLAB was proposed to optimize a standalone PV-BES system with the final excess energy, LPSP and cost as objectives. The simulation results were also benchmarked by HOMER [159]. Furthermore, an optimum control theory-based algorithm was proposed to optimize a PV system with retired EV battery in a residential house with the annual operation cost and PV panel size as objectives [160].

In addition, other important features of hybrid PV-EES systems and individual system components can be treated as optimization criteria. A multi-objective optimization method based on the general algebraic modelling environment was proposed to maximize the station revenue and minimize the battery fading for a PV-EV station [161]. The operation cost and power flow of a PV-wind-diesel system with PHES were treated as optimization targets in [162], and simulation results based on MATLAB showed effective fuel saving in the proposed system. A power flow algorithm and a hybrid multi-objective sensitivity analysis algorithm were adopted to optimize the capacity of storage units for PV systems through the platform of IEEE test feeders. The energy saving, peak load reduction, voltage variation and system capital cost were taken as optimization objectives [163]. Other design optimization criterion relating to the source side has also been studied with a main focus on the system energy efficiency [164].

On the demand side, the environmental effect and indoor thermal comfort are considered as main system evaluation criteria. A lot of research focuses on the environmental contribution of renewable energy systems, because of increased concerns with environment issues. The total annual CO_2 emission (e) can be calculated according to the ε-constraint method [165]:

$$e = \sum_{j\in\alpha} \varepsilon_j \left(\sum_{i\in\beta} \sum_{t=1}^{T} U_{j,i,t} \Delta t\right) \qquad (7)$$

where j is the carrier index; i is the technology index; t is the time index; T is the length of the time horizon; U is the import power; ε is the specific emission coefficient; α is the set of available carriers; and β is the set of available technologies. Two novel mixed-integer linear programming (MILP) models were developed in this study to achieve the cost and emission optimization targets, finding that the optimal MILP models achieved a significant reduction in total annual costs and emissions for the multi-objective optimization problem. Sameti et al. also verified the effectiveness of this optimization method in a net-zero energy district with multiple energy sources and storage technologies. To minimize the total annualized cost and equivalent CO_2 emission, the linear programming (LP) and MILP were utilized to obtain a set of Pareto optima. The result showed that the proposed district energy system performed best economically and environmentally compared with other scenarios [166]. Furthermore, a stochastic optimal energy management was explored with the MILP model to minimize the operation cost and total emission of a microgrid PV system with battery and EV storage units. The energy storage units played an important part in reducing the cost and emission [167]. The carbon emissions and lifecycle costs were minimized for a building in Canada with a hybrid PV-BES system and building envelope renovations. NSGA-II was performed on the platform of EnergyPlus and jEPlus + EA, by which 40% reduction in NPV and 30% reduction in the annual building energy consumption were achieved [168].

Another concerned criterion on the demand side is the indoor thermal comfort, whereas only a few literatures are identified in this area to the best knowledge of the authors. Two conflicting objectives, namely the cost and comfort, were simultaneously optimized for a smart building with an on-grid PV-BES system. A collaborative approach was proposed for system planning and operation [169]. In addition, the occupant comfort and system cost of an experimental room were optimized with three programmed models including a simplified thermal model (STM), STM based genetic algorithm, and EnergyPlus based genetic algorithm [170].

On the grid side, the interaction between the grid and PV-EES systems is the major concern. NSGA-II was adopted to conduct a multi-objective optimization of the grid energy loss, total electricity generation cost and greenhouse gas emission for a practical distribution network in Italy. The study investigated different EES strategies for renewable energy systems including the PV strategy, voltage profile strategy and load strategy, where the voltage profile strategy outperformed others [171]. Based on the residential load and PV storage profiles in typical German households, a MILP model was developed to minimize the grid-purchase electricity cost. Incentives for residential PV-BES systems were also proved to have a promising effect [172]. There are also studies focusing on the interactive effect between the grid and PV-EES systems, such as reducing the reverse power flow to smooth the utility grid with connected renewable energy systems [173].

4.3. Discussion on optimization of hybrid photovoltaic-electrical energy storage systems

Table 6 summaries the widely applied optimization methods for hybrid PV-EES systems, including PSO, E-PSO, GA, SFL, HS, ABC, FP, FA, MOSaDE, NSGA-II, LP and MILP. It is shown that GA is widely applied in searching for multiple possible solutions, but it is relatively less efficient in finding reliable solutions for optimizing hybrid PV-EES systems. The HS algorithm is reported to have better optimization performance than GA with good exploitation, but it may lead to a premature convergence. Although PSO has high convergence speed than GA, it still tends to be trapped in local optima. Improvement of PSO is made by developing algorithms such as E-PSO, SFL and FP for more effective and faster convergence. Moreover, multi-objective optimization problems for hybrid PV-EES systems often adopt MOSaDE, NSGA-II, LP and MILP.

Table 6. Comparison of optimization methods for hybrid PV-EES systems

Optimization methods	Hybrid systems	Optimization objectives	Optimization performance
Particle Swarm Optimization (PSO) algorithm	PV-PHES system [133] PV-wind-BES system [132, 135, 155]	daily cost [132, 133] system reliability and total present cost [155]	high speed convergence [138] faster computation than GA [157] maybe trapped in local solutions [174]
Evolutionary Particle Swarm Optimization (E-PSO) algorithm	PV-wind-BES based system [138]	minimum total annual cost [138]	effective convergence less iteration time than DE, PSO, GA, HSA [138]
Genetic Algorithm (GA)	PV-wind-BES system [132] PV-BES system [145, 151, 170] PV-wind-PHES system [156]	daily operating cost [132] levelized cost of electricity [145] lifecycle cost [151] loss of power supply probability and lifecycle cost [156] thermal comfort and daily cost[170]	easy to solve problems of multiple solutions, and relative low speed [175]
Shuffled Frog Leap (SFL) algorithm	PV-wind-BES system [135]	weekly and daily operational cost [135]	better convergence and lower operational costs than PSO [135]
Harmony Search (HS) algorithm	PV-BES system [136, 143]	daily electricity cost and saving [136] net present value [143]	get improved results than GA [136] good exploitation but may lead to a premature convergence [147]
Artificial Bee Colony (ABC) algorithm	PV-biomass-BES system [144]	net present value [144]	needed more execution time than FP, HS, ABC and FA [144]
Flower Pollination (FP) algorithm	PV-HES system [141] PV-wind-HES [142]	net present value [141, 142]	more efficient and robust than ABC and PSO [141]

Optimization methods	Hybrid systems	Optimization objectives	Optimization performance
Firefly Algorithm (FA)	PV-biomass-BES system [144]	net present value [144]	more efficient than FP, HS, ABC [144]
Multi-Objective Self-Adaptive Differential Evolution (MOSaDE) algorithm	PV-wind-diesel-BES system [157]	cost of electricity and loss of power supply probability [157]	applicable for multi-objective optimization problems [157]
Non-dominated Sorting Genetic Algorithm-II (NSGA-II)	PV-CAES system [158] PV-BES system [168] PV-geothermal-BES based system [171]	investment cost and exergy efficiency [158] carbon emissions and lifecycle costs [168] grid energy loss, total electricity generation cost and greenhouse gas emission [171]	feasible for multi-objective optimization [158]
Linear Programming (LP) model	PV-BES based system [166]	total annualized cost and equivalent CO_2 emission [166]	applicable for solving complex problem [175]
Mixed-integer Linear Programming (MILP) model	PV-wind-BES based system [165] PV-BES-EV system [167] PV-BES system [172]	total annual costs and carbon dioxide emissions [165] daily operation cost and total emission [167] grid-purchase electricity cost [172]	favored as optimization framework for multi-energy system design with a reasonable computational complexity [172]

Table 7 summarizes and compares the major research focus on the optimization of hybrid PV-EES systems in terms of performance assessment criteria. It can be clearly seen that the primary optimization criterion is the cost, covering different indicators such as the daily cost, annual cost, NPV, LCOE and lifecycle cost. And other important single criteria such as the loss of load probability, power delivery and system flexibility, although not so frequently, are also investigated in some research. Much attention has been paid to multi-criterion optimizations of hybrid PV-EES systems to combine the cost with other indicators from source, demand and grid sides.

Table 7. Major recent research focus on the optimization of hybrid PV-EES systems

Mono-criterion optimization	Multi-criterion optimization (on top of cost)		
	Source side (energy supply)	Demand side (energy consume)	Grid side (energy regulate)
daily operation cost [131-136]	loss of load probability [155-157, 159]	CO_2 emission [165, 166]	grid energy loss [171]
annual cost [137-140]	component sizing [160]	CO_2, NO_X, SO_X emissions [167]	grid electricity price [172]
net present value [141-144]	battery fading [161]	carbon emissions [168]	grid smooth [173]
levelized cost of electricity [145, 146]	power flow [162]	indoor thermal comfort [169, 170]	
lifecycle cost [147-151]	peak load reduction [163]		

Mono-criterion optimization	Multi-criterion optimization (on top of cost)		
	Source side (energy supply)	Demand side (energy consume)	Grid side (energy regulate)
loss of load probability [152]	exergy efficiency [158]		
power delivery [153]	energy efficiency [164]		
flexibility [154]			

Based on the above discussion, some research gaps are identified in the optimization of hybrid PV-EES systems for power supply to buildings.

(1) Optimizations of hybrid PV-EES systems can be further conducted to obtain higher building resilience and intelligence, considering the human behavior and thermal comfort of various functional space to sufficiently address occupant preferences in urban context.

(2) Different decision-making techniques with varied weighting strategies should also be investigated for multi-criterion optimizations to derive a robust design for power supply to buildings. Moreover, more detailed optimization studies should be conducted to explore the most suitable setting of each selected algorithm (e.g. NSGA-II, PSO) for achieving robust design solutions for PV-EES systems.

5. Conclusion and outlook

Hybrid PV-EES systems are promising technologies to facilitate renewable energy penetration and achieve building energy autonomy with a booming application market. This study provides an overview of the recent development of hybrid PV-EES systems for power supply to buildings in terms of the global application status as well as the research progress on the system performance and design optimization. The following findings and research gaps are identified to promote the application of PV-EES technologies in buildings.

(1) The lithium-ion battery, supercapacitor and flywheel energy storage technologies show promising prospects in storing PV energy for power supply to buildings, with the applicable storage capacity, fast response, relatively high efficiency and low environmental impact. However, further efforts are required to lower the cost for wider applications in buildings. More research should be conducted to improve materials and configurations of these promising PV-EES technologies for cost competitiveness. Besides, it is significant to investigate the synergetic operation of these applicable PV-EES technologies with buildings for higher energy efficiency.

(2) Hybrid PV-EES technologies aimed at building power supply have specific requirements on the application conditions such as the geography, weather, storage scale and building load. It is suggested to comprehensively consider

local conditions from the source side, demand side and grid side when investigating the technical, economic and environmental feasibilities.

(3) Control strategies supervising the power distribution among all components including the PV panel, EES unit, building and utility grid should be further studied to achieve reliable, efficient, flexible and smart building management. Theoretical control algorithms should be established to address the synergistic operation of these major components.

(4) Interaction between hybrid PV-EES systems and utility grid needs further in-depth investigations. Comprehensive and reliable grid integration indicators should be developed for pragmatic application scenarios. Both the single building and building cluster should be studied to assess the impact of PV-EES systems on the utility grid. The application of on-grid PV-EES systems for building power supply will facilitate an enlarged penetration of PV into urban areas and mitigate the peak demand on the utility grid. Economic analyses on the grid tied PV-EES systems should also be carried out to guide policy makers to develop more effective incentive strategies to encourage the commercialization of PV-EES technologies.

(5) Optimizations of hybrid PV-EES systems can be further conducted to obtain higher building resilience and intelligence, considering the human behavior and thermal comfort of various functional space to sufficiently address occupant preferences in urban context.

(6) Different decision-making techniques with varied weighting strategies should also be investigated for multi-criterion optimizations to derive a robust design for power supply to buildings. Moreover, more detailed optimization studies should be conducted to explore the most suitable setting of each selected algorithm (e.g. NSGA-II, PSO) for achieving robust design solutions for PV-EES systems.

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Nomenclature

ABC: Artificial Bee Colony

BES: battery energy storage
CAES: compressed air energy storage
DE: Differential Evolution s
EES: electrical energy storage
EV: electric vehicle
FA: firefly algorithm
FES: flywheel energy storage
FP: Flower Pollination
GA: genetic algorithm
HES: hydrogen energy storage
HS: Harmony Search
LCOE: low levelized cost of energy
LP: linear programming
LPSP: loss of power supply probability
MILP: mixed-integer linear programming
MOSaDE: Multi-Objective Self-Adaptive Differential Evolution
NPV: net present value
NSGA-II: Non-dominated sorting Genetic Algorithm-II
PHES: pumped hydro energy storage
PSO: Particle Swarm Optimization
PV: photovoltaic
SCES: supercapacitor energy storage
SFL: Shuffled Frog Leap

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