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Review

Towards sustainable solar energy solutions: Harnessing supercapacitors in PV systems

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Abstract: The integration of supercapacitors in photovoltaic (PV) energy systems holds immense potential for enhancing energy storage, reliability, and efficiency. This article provides a comprehensive overview of recent advancements, challenges, and opportunities in the utilization of supercapacitors within PV systems. Fundamental principles of supercapacitor operation, including charge storage mechanisms and electrode materials, are discussed, highlighting their unique advantages such as high power density and rapid charge/discharge capabilities. Various integration strategies, including parallel and series configurations, as well as system-level control algorithms, are examined to optimize energy management and performance. Case studies and real-world examples demonstrate the effectiveness of integrated PV and supercapacitor systems across different applications and scales. According to the results of the research, 235 publications have been made on the subject in the last fifteen years and the number of publications has doubled in the last five years. Additionally, future research directions focus on improving energy density, efficiency, and cost-effectiveness, as well as addressing challenges related to temperature sensitivity and system scalability. Overall, the integration of supercapacitors in PV systems offers promising solutions for advancing sustainable energy solutions and accelerating the transition towards a cleaner, greener future.

Keywords: energy storage; PV power; supercapacitors

1. Introduction

The global demand for sustainable energy solutions continues to escalate in response to environmental concerns and the imperative to mitigate climate change. Among renewable energy sources, solar power stands out as one of the most promising avenues for meeting this demand due to its abundant availability and minimal environmental impact. Photovoltaic (PV) systems, which convert sunlight directly into electricity, have witnessed significant advancements in efficiency and cost-effectiveness over the years, driving their widespread adoption in both residential and commercial settings. However, despite the remarkable progress made in PV technology, one of the persistent challenges facing solar energy systems is the intermittent nature of sunlight. Fluctuations in solar irradiance throughout the day and variations in weather conditions can lead to inconsistent energy output, limiting the reliability and stability of PV installations. As a result, effective energy storage solutions are indispensable for ensuring the continuous availability of solar power, especially during periods of low sunlight or high demand.

Supercapacitors, also known as electrochemical capacitors or ultracapacitors, have emerged as promising candidates for addressing the energy storage requirements of PV systems. Unlike conventional batteries, which store energy through chemical reactions, supercapacitors store electrical energy through the physical separation of charges at the interface between electrodes and electrolytes. This mechanism allows supercapacitors to deliver rapid charge and discharge cycles, high power density, and a long cycle life, making them well-suited for applications requiring frequent and rapid energy exchanges.

Main contributions of this study are:

1) The article consolidates existing knowledge on the integration of supercapacitors in photovoltaic (PV) systems, providing readers with a comprehensive overview of the topic. By synthesizing information from a variety of sources, the article serves as a valuable resource for researchers, engineers, policymakers, and other stakeholders interested in sustainable energy solutions.
2) The article identifies and discusses the advantages and challenges associated with integrating supercapacitors in PV systems. By highlighting the benefits of this approach, such as improved energy management, reliability, and efficiency, as well as addressing potential obstacles such as cost and energy density limitations, the article provides readers with a balanced understanding of the topic.
3) The article explores recent advancements in supercapacitor technology and presents case studies of integrated PV and supercapacitor systems. By showcasing real-world examples and highlighting innovative solutions, the article offers insights into the practical implementation and performance of integrated systems across different applications and scales.
4) The article identifies future research directions and opportunities for further innovation in the field of integrated PV and supercapacitor systems. By discussing emerging technologies, research priorities, and areas for collaboration, the article guides readers towards promising avenues for advancing the state-of-the-art and driving the adoption of sustainable energy solutions.
5) The article informs decision-making and policy development by providing evidence-based insights into the potential benefits and challenges of integrating supercapacitors in PV systems. Policymakers and industry stakeholders can use this information to formulate strategies, allocate resources, and support initiatives aimed at promoting the adoption of renewable energy technologies and enhancing energy sustainability.

In this context, the reminder of this paper as follows: in the first section, the importance of the supercapacitors is highlighted and main contributions of the study is expressed. In the second section, Information is given about the working principle and types of supercapacitors. Then, the integration of supercapacitors into PV energy systems is examined and various studies on the subject are presented. Then, advantages and challenges of the supercapacitors are investigated. After that, recent developments and key studies about supercapacitors usage of PV energy systems are presented. Then, it is attempted to shed light on the future direction of studies on supercapacitors. In conclusion section, the studies carried out over the years are given and the subject is summarized. The overview of the study is given in **Figure 1**.

Figure 1. The overview of the study.

By harnessing the complementary strengths of supercapacitors and photovoltaics, it is aimed to pave the way towards more resilient, efficient, and environmentally sustainable solar energy systems. Through this exploration, a future is envisioned where renewable energy sources like solar power, supported by advanced energy storage technologies such as supercapacitors, are seen to play a central role in the global transition towards a cleaner and more sustainable energy landscape.

2. Fundamentals of supercapacitors

Supercapacitors, also known as ultracapacitors or electrochemical capacitors, represent a class of energy storage devices that bridge the gap between traditional capacitors and batteries. Unlike batteries, which store energy through chemical reactions, supercapacitors store electrical energy through the physical separation of charges at the interface between electrodes and an electrolyte. This mechanism allows supercapacitors to achieve exceptionally high power density and rapid charge/discharge capabilities, making them ideal for applications requiring quick bursts of energy.

At the heart of a supercapacitor lies its unique electrode structure, typically composed of porous materials with a high surface area. Common electrode materials include activated carbon, carbon nanotubes, and graphene, which provide ample surface area for charge accumulation and facilitate efficient charge transfer. The electrolyte, often an aqueous or organic solution containing ions, serves as the medium for ion transport between the electrodes, enabling the storage and release of electrical energy. Özada et al. [1] defined the working principles and characteristics of supercapacitors in energy storage systems.

Supercapacitors can be broadly classified into two main types based on their electrode materials and electrolyte composition: electrochemical double-layer capacitors (EDLCs) and pseudocapacitors. EDLCs store energy primarily through the physical adsorption of ions at the electrode/electrolyte interface, relying on the formation of an electric double layer. Pseudocapacitors, on the other hand, exhibit additional electrochemical redox reactions at the electrode surface, leading to enhanced energy storage capacities compared to EDLCs.

An EDLC has two non-reactive porous electrodes immersed in an electrolyte, with a separator between the electrodes that permits the movement of the ions through it. The energy is stored by charge separation in an electrochemical double layer, formed at the electrode/electrolyte interface [2]. The internal structure of an EDLC is given in **Figure 2**. Energy storage occurs through the process of charge separation within an electrochemical double layer, which materializes at the interface between the electrode and the electrolyte. The thickness of this double layer is intricately influenced by factors such as the electrolyte concentration and the dimensions of the ions involved, typically ranging between 0.5 to 1 nanometer in the case of concentrated electrolytes. The ions necessary for charging the electrochemical double-layer capacitor are transported between the porous electrodes via diffusion through the electrolyte.

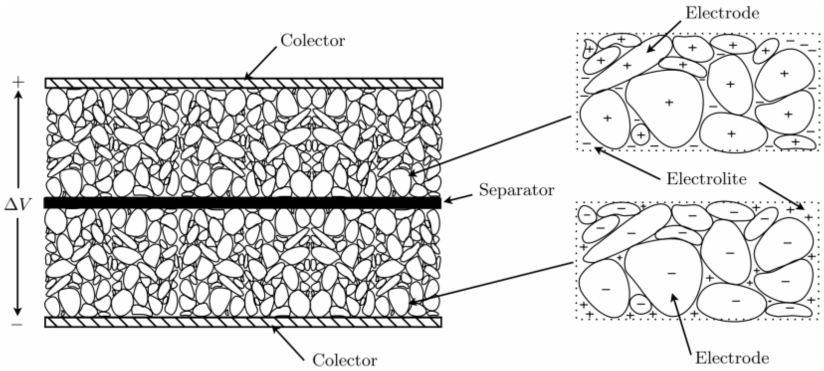

Figure 2. Internal structure of EDLC [2].

The use of activated carbon electrodes and the limitations on voltage and accessible surface area is discussed in another study [3]. **Figure 3** represents the schematic of an activated carbon-based EDLC and electron micrograph of an activated carbon electrode. The combination of a minute charge separation within the double-layer and the extensive surface area of the electrode leads to a specific capacitance typically ranging from 40 to 60 farads per cubic centimeter (F/cm^3). Moreover, the breakdown field strength of the EDLC expressed in volts per centimeter (V/cm), is notably elevated compared to conventional capacitors. These three factors—namely, the large surface area, minimal charge separation, and heightened field strength—contribute to the remarkable energy density achievable with the EDLC.

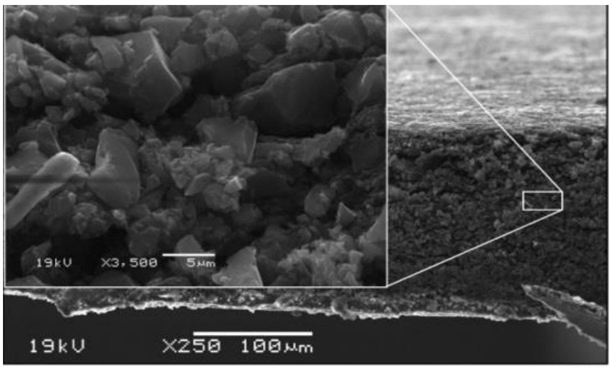

Figure 3. Electron micrograph view of activated carbon electrode [3].

One of the defining characteristics of supercapacitors is their remarkable cycle life, which far exceeds that of conventional batteries. Unlike batteries, which degrade over time due to chemical reactions and electrode wear, supercapacitors undergo minimal degradation even after hundreds of thousands or millions of charge/discharge cycles. This longevity, combined with their rapid response times and high efficiency, makes supercapacitors well-suited for applications requiring frequent and prolonged operation, such as renewable energy systems and electric vehicles.

Kamali et al. [4] evaluated the environmental impact of two supercapacitor designs in a prospective life cycle assessment conducted at a later stage. Jiang et al. [5] utilized a life cycle assessment method to examine the environmental performance of a nitrogen-doped biochar aerogel-based electrode (BA-electrode) derived from Entermorpha prolifera. Torregrossa and Paolone [6] introduced a novel experimental approach to investigate the ageing mechanisms affecting supercapacitors. Their study outlines a carefully designed procedure aimed at assessing the ageing process through combined life endurance and power cycling tests. Specifically, their study evaluates the impact of temperature (referred to as life endurance) on supercapacitors subjected to a predetermined power cycle. Additionally, their investigation delves into the effects of temperature during the recovery phase. Cossutta et al. [7] conducted a comprehensive assessment, covering the entire lifecycle of graphene applications. Specifically, it focuses on a case study involving the manufacturing of supercapacitors utilizing graphene and activated carbon as active materials. Tankari et al. [8] used the Rainflow Cycles Counting Method to estimate the supercapacitors lifetime.

Li et al. [9] prepared a redox-active organic molecular electrode for supercapacitors. In their study, the researchers investigated the adsorption of Benzo[1,2-b:4,5-b'] dithiophene-4,8-dione (BDTD), a planar molecule with a fused heteroaromatic structure, onto conductive reduced graphene oxide (rGO) through pi-pi interactions. This process resulted in the formation of a three-dimensional interconnected and functionalized xerogel, referred to as BDTD-rGO. Consequently, the optimized BDTD-rGO electrodes demonstrated a specific capacitance of 360 Fg^{-1} at 1 Ag^{-1}, coupled with an exceptionally long cycle life, retaining 96.4% of their capacitance after 10,000 cycles and still maintaining 80% after 50,000 cycles at 5 Ag^{-1} in 1 M H_2SO_4.

Glogic et al. [10] used coconut shells to produce high-performance activated carbon electrodes for energy storage super-capacitors. Their analysis was carried out using the life cycle assessment approach to investigate the production of activated carbon material and resulting electrodes for a broad range of environmental impact categories and energy use.

Murray and Hayes [11] presented the results of a study on super-capacitor lifetime. Cycle testing was carried out on individual supercapacitors at room temperature and at rated temperature utilizing a thermal chamber and equipment programmed through GPIB and MATLAB. The results of their study demonstrate cycle lifetimes significantly in excess of manufacturer specifications and potential for deployment in long-life robust applications. **Figure 4** represents the capacitance versus cycle number of a supercapacitor during application testing at 25 ℃. The application study anticipates approximately one million cycles for a full-scale energy storage system comprising supercapacitor modules. Assuming the same cycle lifetime degradation observed in the tested single supercapacitor (excluding other aging factors), it is projected that the system could operate at sea for an estimated duration of 34 years.

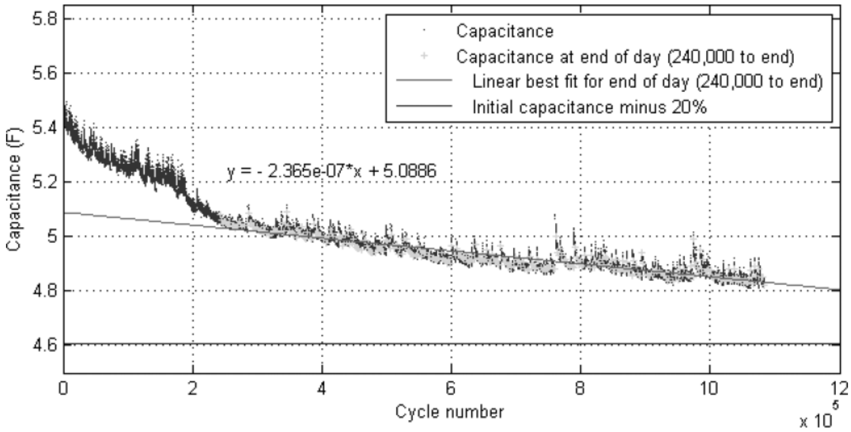

Figure 4. Capacitance versus cycle number of a supercapacitor during application testing at 25 ℃ [11].

In summary, supercapacitors offer a unique set of advantages, including high power density, rapid charge/discharge capabilities, long cycle life, and robust performance under diverse operating conditions. Understanding the fundamental principles underlying supercapacitor operation is essential for harnessing their full potential in various energy storage applications, including their integration into photovoltaic systems for enhanced performance and reliability.

3. Integration of supercapacitors in PV systems

The integration of supercapacitors with photovoltaic (PV) systems offers a promising avenue for overcoming the intermittent nature of solar energy and improving overall system performance. By storing excess energy generated during periods of high sunlight and delivering it during periods of low irradiance or high demand, supercapacitors enable PV systems to achieve greater energy autonomy and reliability. The integration of supercapacitors can be realized through various configurations, including parallel or series connections with PV modules, as well as system-level integration with power electronics and control systems.

In a parallel configuration, supercapacitors are connected in parallel with PV modules, allowing them to capture surplus energy generated by the solar panels and store it for later use. This approach enhances the overall energy management of the system, reducing dependence on the grid and maximizing self-consumption of solar energy. Additionally, supercapacitors can serve as buffer devices to smooth out fluctuations in PV output caused by factors such as shading, clouds, or variations in solar irradiance, thereby improving system stability and efficiency.

Zhang et al. [12] connected an appropriate supercapacitor in parallel with the PV system in order to further mitigate the fluctuations for PV system. The simulation results demonstrated the designed supercapacitor structure has a better performance than the conventional structures.

Keshavarzi and Ali [13] introduced an integrated and cost-effective photovoltaic-supercapacitor (PVSC) system, merging the energy storage capability of the supercapacitor (SC) directly into the PV array. This integration facilitates bidirectional power flow, ensuring system stability during grid disturbances occurring throughout the day, night, and under cloudy conditions. The efficacy of this system was assessed through simulation analysis and compared against that of a basic PV system and a conventional SC system, where the full energy storage is parallel-connected with the PV. The results indicate that the proposed PVSC system enhances the dynamic performance of the grid system it is connected to. **Figure 5** shows a parallel supercapacitor structure.

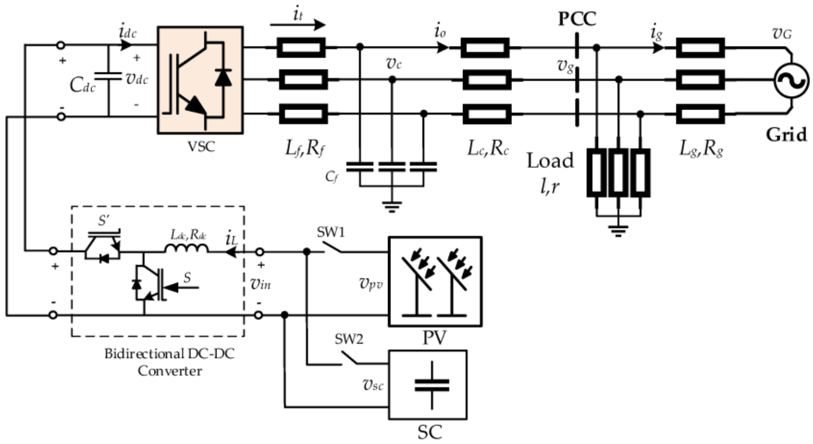

Figure 5. Power stage of a PV-supercapacitor energy storage system [13].

In a series configuration, supercapacitors are connected in series with the PV modules, typically through a DC-DC converter or charge controller. This setup enables the supercapacitors to store energy at a higher voltage level, enhancing their energy storage capacity and efficiency. By storing energy at a higher voltage, supercapacitors can minimize energy losses during charging and discharging cycles, leading to improved overall system performance and energy yield. Series-connected supercapacitors can also provide voltage support and regulation, ensuring optimal operation of the PV system under varying load conditions.

System-level integration of supercapacitors with PV systems involves the incorporation of advanced power electronics and control algorithms to optimize energy management and performance. This may include the use of maximum power point tracking (MPPT) algorithms to maximize energy harvest from the PV array, as well as intelligent energy management systems to dynamically allocate energy between the PV modules and supercapacitors based on real-time demand and operating conditions. Such integration schemes enable PV systems to operate more efficiently and autonomously, reducing reliance on external energy sources and enhancing overall system resilience.

Han et al. [14] conducted research on a sizeable dispatchable grid-connected photovoltaic (PV) system designed to feed power directly into the grid for centralized dispatch, rather than supplying electricity solely to a local load. To optimize the utilization of solar energy, the system incorporates a hybrid electricity storage solution comprising both batteries and supercapacitors alongside the PV array.

Sahin and Blaabjerg [15] investigated and analyzed the advantages of incorporating supercapacitors in a hybrid energy storage system. Their study proposes a hybrid system that harnesses photovoltaic energy and stores it using both batteries and supercapacitors, aiming to address key challenges on both fronts. Using MATLAB/Simulink, they designed models for the supercapacitor, photovoltaic system, and the proposed hybrid setup rated at 6 kW. **Figure 6** illustrates MATLAB/Simulink model of a supercapacitor. Additionally, they introduced a novel topology aimed at enhancing energy storage capacity with supercapacitors in a passive storage setup. This topology focuses on temporarily storing instantaneous peak currents in supercapacitors, leading to voltage stabilization on both ends and reducing the load on batteries. Consequently, this approach extends battery lifespan and reduces overall system costs.

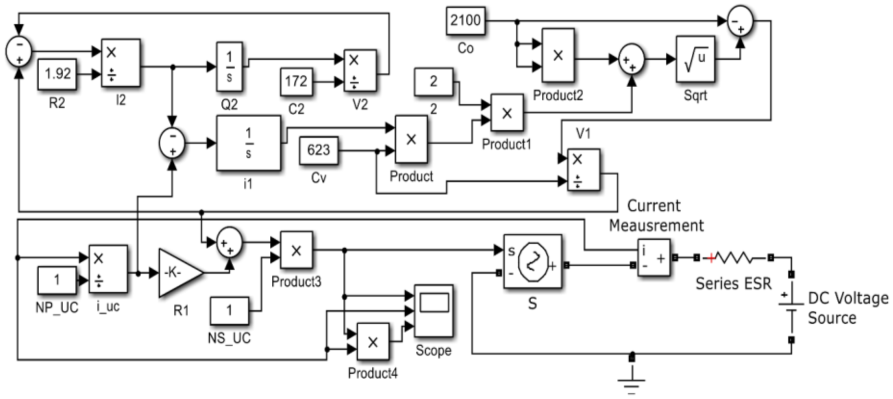

Figure 6. MATLAB/Simulink model of a supercapacitor [15].

Yang and Hu [16] introduced an innovative dynamic inertia control strategy for supercapacitors in multi-area autonomous microgrid (MG) clusters, utilizing a fuzzy-based approach. Javadpoor and Nazarpour [17] explored a hybrid photovoltaic (PV)-hydrogen/fuel cell (FC) system comprising fundamental components such as a PV array, a fuel cell, alkaline water electrolysis, and a hydrogen storage tank. Zhao et al. [18] introduced a multiobjective optimization approach for electric vehicle-supercapacitor hybrid energy storage systems aimed at aligning with the output of photovoltaic projects. Sabhahit et al. [19] outline control strategies tailored for a hybrid power system integrating photovoltaics, fuel cells, and a supercapacitor bank, designed for use in isolated load scenarios. Tummuru et al. [20] have introduced rapid-response DC-link voltage-dependent energy management strategies designed for a hybrid energy storage system powered by solar photovoltaic (PV) energy.

Hossain et al. [21] outlined a comprehensive approach involving the design and execution of a universal ramp-rate-based compensation technique. This strategy is aimed at stabilizing solar power output and swiftly meeting sudden load demands within grid-connected microgrids. It leverages a hybrid multilevel storage system incorporated into the DC link of the power converter. This system includes high-capacity buffer storage like battery systems and hydrogen storage, comprising a proton exchange membrane electrolyzer and a fuel cell. Additionally, short-term cache storage such as supercapacitors is employed to enhance system efficiency.

Xiong and Nour [22] acknowledged the importance of energy storage by conducting simulations of a comprehensive PV-battery-supercapacitor model using MATLAB/Simulink. This simulation aimed to generate a flat load profile, enhancing predictability from a network management perspective. Regowski et al. [23] provided findings from measurements and parameter comparisons of an energy storage system comprising supercapacitor batteries and a conventional lead-acid solution. This system was specifically tailored for use in photovoltaic micro-installations. Given the lack of dependable and cost-effective PV module characterization systems, the development and analysis of a smart, digital, and portable test setup is of considerable importance. Pal et al. [24] have addressed this need by devising and evaluating such a model in their study. In their setup, supercapacitors serve as the load for the photovoltaic module being tested.

Abbassi et al. [25] have introduced a novel approach for optimally determining the size of a hybrid energy storage system (HESS) using a statistical method. This method is designed to leverage the capacity distribution of a hybrid supercapacitor-battery system within an autonomous photovoltaic (PV)/wind power generation setup.

Palla and Kumar [26] introduced an algorithm designed to coordinate the control of photovoltaic systems and ultracapacitor-based energy storage systems. Their proposed system is shown in **Figure 7**. The aim is to mitigate the impacts of abrupt variations in solar irradiance and address low voltage occurrences at the point of common coupling. Furthermore, their study presents an enhanced multi-mode operational scheme for controlling ultracapacitor-based energy storage systems. This scheme accounts for various constraints associated with both charging and discharging modes.

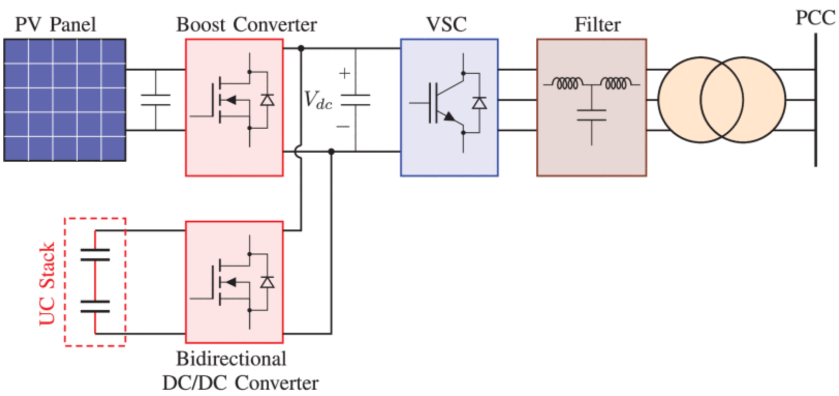

Figure 7. Configuration of a typical PV-Ultracapacitor system.

Benavides et al. [27] have introduced a power smoothing technique employing supercapacitors within a grid-connected photovoltaic system. This method operates through two distinct stages: prediction and correction, aimed at enhancing power stability.

Roy et al. [28] investigated a HESS integrating both a battery and a supercapacitor for managing solar power dispatch in hourly increments over a full day for 1 MW grid-connected PV arrays. The HESS operates autonomously, utilizing the PV array for charging rather than relying on grid power, ensuring immunity to fluctuations in electricity prices. While the battery and supercapacitor are designed to deliver consistent predetermined power levels, their primary function does not include providing ancillary services for grid operation.

In summary, the integration of supercapacitors in PV systems offers significant benefits in terms of energy storage, management, and system performance. Whether deployed in parallel or series configurations, or integrated at the system level with advanced control strategies, supercapacitors enhance the reliability, efficiency, and sustainability of photovoltaic installations, contributing to the broader transition towards a clean and renewable energy future.

4. Advantages and challenges

The integration of supercapacitors in photovoltaic systems offers a range of advantages that contribute to improved system performance, reliability, and efficiency. One of the key advantages is the rapid charge and discharge capabilities of supercapacitors, which enable them to respond quickly to fluctuations in solar irradiance and load demand. This ability to store and release energy rapidly makes supercapacitors well-suited for applications requiring high-power bursts, such as grid stabilization, frequency regulation, and peak shaving.

Another advantage of supercapacitors is their long cycle life and robust performance under diverse operating conditions. Unlike conventional batteries, which degrade over time due to chemical reactions and electrode wear, supercapacitors undergo minimal degradation even after thousands or millions of charge/discharge cycles. This longevity ensures the reliability and durability of the energy storage system, reducing maintenance requirements and overall lifecycle costs.

Supercapacitors also offer high efficiency and energy density compared to other energy storage technologies, such as batteries. Their high charge/discharge efficiency and low internal resistance result in minimal energy losses during energy conversion processes, maximizing overall system efficiency. Additionally, supercapacitors can achieve high energy densities when combined with advanced electrode materials and electrolytes, further enhancing their energy storage capacity and performance.

Despite these advantages, the integration of supercapacitors in PV systems presents certain challenges and limitations that must be addressed. One of the primary challenges is the relatively low energy density of supercapacitors compared to batteries, which limits their ability to store large amounts of energy over extended periods. This constraint may necessitate the use of hybrid energy storage systems combining supercapacitors with batteries or other storage technologies to achieve the desired energy storage capacity while maintaining high power density and efficiency.

Cost is another factor to consider when integrating supercapacitors into PV systems. While supercapacitors offer long-term cost savings due to their extended lifecycle and minimal maintenance requirements, their initial capital costs can be higher than traditional battery systems. However, ongoing advancements in supercapacitor technology, along with economies of scale in manufacturing, are expected to drive down costs and improve cost-effectiveness over time.

Temperature sensitivity is another challenge associated with supercapacitors, as their performance and lifespan can be affected by temperature variations. Extreme temperatures can degrade electrode materials, reduce electrolyte conductivity, and compromise overall system efficiency and reliability. Therefore, proper thermal management strategies must be implemented to mitigate temperature-related effects and ensure optimal performance of the integrated PV and supercapacitor system.

In summary, while the integration of supercapacitors in PV systems offers numerous advantages in terms of performance, reliability, and efficiency, it also presents certain challenges and considerations that must be addressed. By overcoming these challenges through ongoing research, innovation, and technological advancements, supercapacitors have the potential to play a significant role in enhancing the sustainability and viability of solar energy systems.

5. Recent developments and case studies

In recent years, there have been significant advancements in the development and integration of supercapacitors in photovoltaic systems, driven by a growing demand for reliable and efficient renewable energy solutions. These advancements encompass a wide range of areas, including materials science, device engineering, system design, and control algorithms, aimed at improving the performance, durability, and cost-effectiveness of integrated PV and supercapacitor systems.

One area of innovation in supercapacitor technology is the development of advanced electrode materials with enhanced energy storage capacities and improved electrochemical properties. Researchers have explored novel carbon-based materials, such as carbon nanotubes, graphene, and activated carbon composites, as well as transition metal oxides and conducting polymers, to increase the energy density and power density of supercapacitors. These materials offer higher specific surface areas, greater charge storage capacities, and faster charge/discharge rates, enabling the development of supercapacitors with superior performance characteristics for PV energy storage applications.

Zhang et al. [29] primarily discuss recent progress and obstacles in flexible supercapacitors, with a focus on the synthesis and performance of flexible substrates. Ji et al. [30] emphasized the principle of designing electrode materials, which involves comprehending the connections between the structural design, properties, and components of electrode materials, and how these factors influence their electrochemical performance. Jiang et al. [31] have provided a recent review on carbon-based nanostructured electrode materials, encompassing structures ranging from zero-dimensional to three-dimensional. Their analysis delves into the impact of nanostructuring on supercapacitor properties, such as specific capacitance, rate capability, and cycle stability. The insights gained from this exploration may serve as valuable guidance for the design of electrodes in the development of the next generation of EDLCs. Grace and Ramachandran [32] discussed advancements in the development of nanostructured materials for supercapacitor electrodes. Baig et al. [33] outlined the operational principles and obstacles associated with various advanced materials utilized in supercapacitor electrodes, along with proposed strategies for addressing these challenges.

In addition to material advancements, there have been notable developments in the design and fabrication of supercapacitor devices tailored for integration with PV systems. These include the development of flexible and lightweight supercapacitors compatible with flexible PV modules and building-integrated photovoltaics (BIPV) applications. Such devices offer enhanced mechanical flexibility, conformability, and durability, enabling seamless integration into various architectural and structural elements while maintaining high energy storage performance.

Maddala et al. [34] showcased the remarkable photovoltaic power conversion efficiency (PCE) of 11.12% achieved through single-wall carbon nanohorn-assisted carbon counter electrodes in dye-sensitized solar cells (DSSCs). This efficiency surpassed that of platinum (9.41%), motivating the fabrication of a dye-sensitized solar module (DSSM) comprising six series-connected DSSCs arranged in a bifacial configuration for building-integrated photovoltaic applications. The DSSM achieved an impressive champion PCE of 19.71%. To further enhance this efficiency, an integrated device, termed a photocapacitor, was developed, combining the DSSM with a supercapacitor.

Several case studies and real-world implementations highlight the effectiveness and benefits of integrating supercapacitors into PV systems across different scales and applications. For example, in off-grid and remote areas where access to reliable electricity is limited, standalone PV systems with integrated supercapacitors provide a cost-effective and sustainable energy solution. These systems can store excess solar energy during the day and deliver it during periods of high demand or low sunlight, ensuring continuous power supply for lighting, communication, and other essential services. In grid-connected PV installations, supercapacitors serve as valuable assets for enhancing grid stability, power quality, and energy management. By providing fast response times and high-power support, supercapacitors can mitigate voltage fluctuations, frequency variations, and transient disturbances caused by intermittent renewable energy sources such as solar power. Furthermore, supercapacitors enable grid operators to implement demand response strategies, peak shaving, and energy arbitrage schemes, optimizing the use of renewable energy resources and reducing reliance on fossil fuels.

Hamdan et al. [35] discussed methods to enhance the stability of grid-connected photovoltaic systems by incorporating supercapacitors. **Figure 8** shows their supercapacitor model. Their approach focuses on applying this technique to photovoltaic systems utilizing the perturbation and observation (P&O) algorithm for maximum power point tracking. The P&O algorithm serves to optimize power extraction from the photovoltaic system under study.

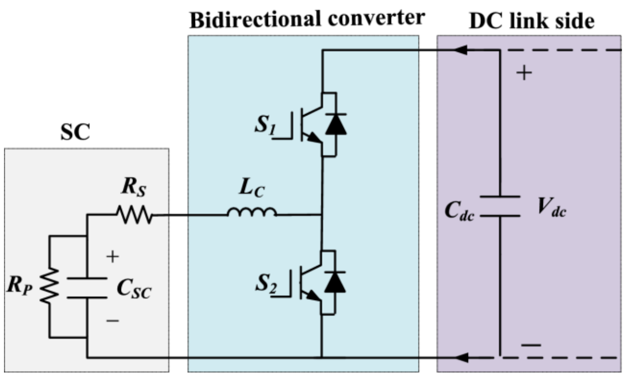

Figure 8. Schematic diagram of the SC model [35].

Vargas et al. [36] introduced a model designed for harmonic transient simulation of a standalone photovoltaic system, incorporating a hybrid energy storage system comprised of batteries and supercapacitors. This model utilizes a newly introduced technique for harmonic domain modeling.

Ramineni et al. [37] have devised and applied an energy management (EM) model to a foundational electric vehicle (EV) model powered by solar energy. Predicting the driver cycle of the EV poses a significant challenge in any EM model. The core structure incorporates solar panels, supercapacitors, batteries, DC-DC converters, and appropriate control models.

Alam et al. [38] introduced a control strategy for supercapacitors within a microgrid composed of multiple clusters integrating various renewable energy sources and generators, including wind power, solar photovoltaics, solar thermal power (STP), fuel cells, aqua electrolyzers, and diesel generators. Initially, they developed a small-signal model to aid in control design. This model was then combined with a fractional-order supercapacitor controller to stabilize the microgrid frequency. Additionally, optimization of controller parameters was conducted to ensure robust performance.

Arkhangelski et al. [39] investigated a Hybrid Renewable Energy System (HRES) as a dependable power supply source when connected to the grid. Grid connection imposes limitations on the power output and harmonic content of the HRES, necessitating the use of multiple control systems and subsystems such as measurement normalization, current control, active harmonic compensation, and synchronization, as detailed in their study. Special emphasis was placed on interactions within the storage system of the HRES. Combining supercapacitors and batteries was identified as a method to enhance the durability of the HRES.

Díaz-González et al. [40], the authors introduced a two-level controller designed to oversee a hybrid energy storage solution for integrating photovoltaic plants into distribution grids. This HESS involves linking a lead-acid battery pack with a supercapacitor pack via a modular power electronics cabinet. **Figure 9** shows the active power results of their study. As depicted, the peak power exchanged with the grid is significantly diminished, ensuring that maximum values remain below 6 kW. Additionally, concerning apparent power, the values remain below the maximum threshold set by grid ratings. This power limitation is achieved through the coordinated operation of both the battery and supercapacitor packs.

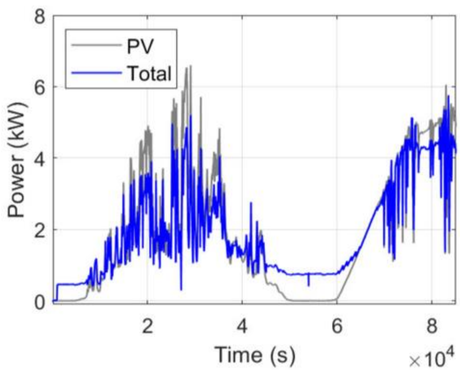

Figure 9. The total active power output of the PV plant with and without the contribution of the hybrid energy storage solution [40].

Mbouteu Megaptche et al. [41], the authors discussed the utilization of a Demand Response-Fuzzy Inference System Controller (DR-FIS) to regulate the operation of loads. This controller was employed for the sizing optimization of systems comprising photovoltaic/wind turbine/battery/supercapacitor and photovoltaic/wind turbine/battery/diesel generator setups, operating autonomously in a health center located in northern Cameroon. The optimization process utilized multi-objective particle swarm optimization (MOPSO) and multi-objective genetic algorithm (MOGA) methods.

Overall, recent developments in supercapacitor technology and case studies of integrated PV and supercapacitor systems demonstrate the potential for these solutions to drive the transition towards a more sustainable and resilient energy future. By leveraging advancements in materials science, device engineering, and system integration, integrated PV and supercapacitor systems offer scalable, reliable, and cost-effective solutions for meeting the growing demand for clean energy worldwide.

6. Future directions and opportunities

As the demand for renewable energy continues to rise and the need for sustainable energy solutions becomes increasingly urgent, the integration of supercapacitors in photovoltaic systems presents exciting opportunities for further innovation and advancement. Looking ahead, several key areas emerge as focal points for future research, development, and implementation of integrated PV and supercapacitor systems.

One area of focus is the continued advancement of supercapacitor technology to improve energy density, power density, and efficiency. Ongoing research efforts aim to develop new electrode materials, electrolytes, and device architectures capable of enhancing the energy storage capacity and performance of supercapacitors while maintaining their fast charge/discharge capabilities and long cycle life. Advances in nanomaterials, hybrid energy storage systems, and manufacturing processes hold promise for achieving breakthroughs in supercapacitor performance and cost-effectiveness.

Another area of interest is the integration of supercapacitors with emerging PV technologies, such as perovskite solar cells, tandem solar cells, and organic photovoltaics. These next-generation PV technologies offer higher efficiency, lower manufacturing costs, and greater flexibility compared to traditional silicon-based solar cells, opening up new opportunities for integrated PV and supercapacitor systems in a variety of applications. By combining the advantages of advanced PV technologies with the energy storage capabilities of supercapacitors, researchers aim to develop highly efficient, lightweight, and cost-effective solutions for distributed energy generation, grid integration, and electrification initiatives.

In addition to technological advancements, future research efforts will focus on addressing key challenges and barriers to the widespread adoption of integrated PV and supercapacitor systems. These challenges include cost competitiveness, system scalability, standardization, and regulatory frameworks. Collaborative research initiatives involving academia, industry, and government agencies are needed to overcome these challenges and accelerate the deployment of integrated PV and supercapacitor systems on a global scale.

Furthermore, the development of advanced control algorithms and energy management strategies will play a crucial role in optimizing the operation and performance of integrated PV and supercapacitor systems. By leveraging real-time data, predictive analytics, and machine learning techniques, researchers can develop intelligent control systems capable of maximizing energy harvest, optimizing energy storage, and minimizing grid impact. These advanced control strategies will enable integrated PV and supercapacitor systems to operate autonomously, adaptively, and efficiently under diverse operating conditions and grid environments.

In summary, the integration of supercapacitors in PV systems holds tremendous potential for shaping the future of renewable energy and accelerating the transition towards a sustainable energy landscape. By focusing on technological innovation, research collaboration, and policy support, stakeholders can unlock new opportunities and overcome barriers to the widespread adoption of integrated PV and supercapacitor systems, paving the way for a cleaner, greener, and more resilient energy future.

7. Conclusions

The integration of supercapacitors in photovoltaic (PV) systems represents a promising approach for addressing the energy storage challenges associated with solar energy and advancing the transition towards a sustainable energy future. Through this exploration, it is evident that supercapacitors offer unique advantages such as high power density, rapid charge/discharge capabilities, and long cycle life, making them well-suited for applications requiring efficient and reliable energy storage. The number of academic publications regarding the use of supercapacitors in PV energy systems has increased over the years. **Figure 10** shows the number of academic publications involving the use of supercapacitors in photovoltaic energy systems in the last fifteen years [42]. Studies on the subject have doubled in the last five years.

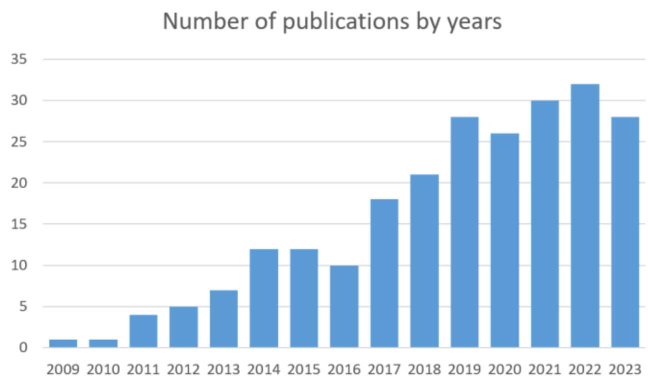

Figure 10. Number of publications by years [42].

By harnessing the complementary strengths of supercapacitors and PV technology, integrated systems can achieve greater energy autonomy, reliability, and efficiency. Supercapacitors enable PV systems to capture surplus energy during periods of high sunlight and deliver it during periods of low irradiance or high demand, thereby enhancing overall system performance and stability. The integration of supercapacitors also facilitates grid integration, demand response, and energy management strategies, enabling PV systems to contribute to grid stability and resilience.

Furthermore, recent developments in supercapacitor technology and case studies of integrated PV and supercapacitor systems demonstrate the feasibility and effectiveness of this approach across a wide range of applications and scales. From off-grid installations in remote areas to grid-connected systems in urban environments, integrated PV and supercapacitor systems offer scalable, reliable, and cost-effective solutions for meeting the growing demand for clean energy worldwide.

Looking ahead, there are exciting opportunities for further innovation and advancement in the field of integrated PV and supercapacitor systems. Future research efforts will focus on enhancing the energy density, efficiency, and cost-effectiveness of supercapacitors, as well as exploring new materials, device architectures, and system integration strategies. Collaborative research initiatives involving academia, industry, and government agencies will be essential for overcoming key challenges and accelerating the adoption of integrated PV and supercapacitor systems on a global scale.

In conclusion, the integration of supercapacitors in PV systems holds tremendous potential for driving the transition towards a more sustainable, resilient, and efficient energy landscape. By leveraging advancements in technology, research collaboration, and policy support, stakeholders can unlock new opportunities and overcome barriers to the widespread adoption of integrated PV and supercapacitor systems, ultimately contributing to a cleaner, greener, and more sustainable future for generations to come.

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