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Energy Sustainability via Integrated Photovoltaic Solar Cells and Supercapacitors: A Comprehensive Review

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ABSTRACT
The conventional method of charging supercapacitors with photovoltaic (PV) technology was initially designed such that solar cells and supercapacitors functioned independently, linked by external wiring. While this architecture allows for simultaneous energy generation and storage, it presents multiple technical complications, such as bulkiness, inflexibility, high expenses, and substantial energy loss due to the connecting wires between the two components. To address these drawbacks, integrating the supercapacitor and PV cell into a unified system can result in a more streamlined, adaptable, and modular design, effectively minimizing energy losses by eliminating the need for external connections. Including supercapacitors in photovoltaic body has great potential to increase energy storage capacity, system efficiency, and reliability. The review examines the newest developments, problems, and future for the use of supercapacitors in photovoltaic systems in great detail. While pointing out their particular benefits, such increased power density and quick charge/discharge rates, it covers basic operational concepts of supercapacitors including charge storage mechanisms and electrode materials. Various integration techniques, including parallel and series setups, have been studied to maximize energy management and total performance together with thorough system-level control methods. Illustrative case studies and practical examples show the success of PV and supercapacitor integration over a range of uses and scales. Recent research show that scholarly literature on this topic is increasing, therefore highlighting the growing curiosity in this area. Furthermore, future studies will concentrate on boosting energy density, efficiency, and cost-effectiveness as well as solving problems like temperature sensitivity and scalability of the devices. Therefore, adding supercapacitors inside PV systems offers a great way to help in the great decrease of global warming effects and support sustainable energy developments.

Keywords:
Energy sustainability,
PV solar cell,
Supercapacitor,
Energy Storage,
PV Power.

INTRODUCTION

Growing worldwide preference for sustainable energy sources reflects a reaction to rising environmental issues and urgent need to solve climate change. Among the range of renewable energy alternatives, solar energy stands out for its great availability and little environmental effect. Photovoltaic (PV) technology, which converts sunshine into electricity, has seen great improvements in its efficiency and economic feasibility over the years, hence encouraging its widespread use in both residential and commercial spheres. Still, the occasional availability of sunshine presents a major problem (Ibrahim, 2026). Fluctuations in energy output can result from variations in solar radiation throughout the day, together with shifting meteorological conditions, therefore jeopardizing the dependability and uniformity of PV systems (Salameh et al., 2021). Particularly during times of inadequate sunlight or great energy demand, this draws attention to the urgent necessity of efficient energy storage systems to ensure a steady supply of solar energy. The traditional method for charging supercapacitors using photovoltaic (PV) technology was initially conceived with solar cells and supercapacitors functioning as distinct components linked via wiring. Although this configuration allows for concurrent energy generation and storage, it presents several technical obstacles, including bulkiness, rigidity, high costs, and significant energy loss through external connections between the components (Czagany et al., 2024). By combining the supercapacitor and PV cell into one gadget, one can create a compact, flexible, modular system that reduces energy loss as no cabling is needed. These drawbacks can be lessened. Promoting space efficiency, practical use, and versatility across many industries—including both small and big consumer electronics, electric cars, smart grids, wearable sensors (Scalia et al., 2017). This invention fits contemporary smart technology trends. Historically employed in conjunction with PV cells, batteries have been replaced as the ideal option for incorporation owing to performance restrictions including slow charge/discharge rates and short lifespan. (Salameh et al., 2021). This preference is due to their rapid charge/discharge capabilities, which are facilitated by the lack of chemical reactions and a reported energy density approximately ten times that of equivalent-weight batteries. Extensive research interest has followed the PV cell-supercapacitor integration concept's debut, leading to several experimental and simulation investigations meant to assess the construction and performance of such systems. One such system, for instance, integrated light-emitting diodes (LEDs) with nickel-cobalt oxide (NiCo2O4) battery-supercapacitor hybrids and hydrogenated amorphous silicon (a-Si/H) solar cells. With a general efficiency of around 9% and a high storage efficiency, the system showed independent behavior that suggests equilibrium in both PV conversion and energy storage. Achieving best efficiency from supercapacitors and solar panels depends on prior analytical studies of them (Sachin et al., 2017). Functioning of supercapacitors is quite dependent on the electrode materials employed, hence the investigation of these materials is a key concentration of this area of study. Consumers progressively depend on energy solutions to satisfy their electronic needs as technology changes quickly. Being a renewable resource, solar energy may be gathered worldwide wherever the available technology is. It entails converting sunlight into electrical power fit for both household and industrial uses. An energy storage system is vital to avoid energy loss during operations, and supercapacitors are especially helpful owing their quick charge/discharge properties and long lifespan in addition to clean energy generation. Compared to batteries, supercapacitors provide higher energy conversion rates and lower equivalent series resistance, positioning them as effective energy storage solutions for solar panel applications(Scalia et al., 2017; Sachin et al., 2017; Yuan et al., 2019; Vega-Garita et al., 2019; Chuang et al., 2020; Zhong et al., 2017; Piyumal et al., 2021 ; Shen, 2021).Though adding energy storage devices could thicken the cell, the overall compactness attained and decrease in system volume make this more desirable than preserving distinct units. External linkages are known to frequently result in greater resistances, stiff structures, and sophisticated manufacturing methods. While retaining their durability and quick charge/discharge capacity (Piyumal et al., 2021 & Shen, 2021), the main difficulty in designing supercapacitors is boosting their energy and power density. Therefore, including these tools offers both pragmatic prospects and improves their efficiency. The fast development of smart technologies is recognized, propelled by the need for portable and flexible energy storage solutions from the electronics industry. An example is the construction of a high-performance hybrid supercapacitor using nickel-cobalt layered double hydroxide (LDH) as the cathode and crushed leaf-like reduced graphene oxide as the anode, with 3D dendritic cell-like nanostructures. Reaching an operational potential window of about 2V and with power and energy densities commensurate with current density, in this supercapacitor connected with a solar cell for energy harvesting highlights the great possibility for energy and power density when these devices are used asymmetrically. High coulombic efficiency also helped the supercapacitor's performance. (Zhong et al., 2017). With supercapacitors functioning as the energy transport systems, from the papers evaluated it is clear that solar cells efficiently capture solar energy and transform it into electricity. Selecting appropriate active materials for integrated device construction is essential to maximize conversion efficiency. As these materials greatly affect energy conversion efficiency and eventually improve the operating performance and lifetime of PV cell-integrated supercapacitors (Lechêne et al, 2016), counter electrodes, conductive polymers, photoactive metal oxides, and redox electrolytes are critical parameters worthy of consideration. Interest among scientists has exploded for more investigation into the creation of solar-cell-integrated supercapacitors with superior characteristics given the encouraging efficiencies and flexibility demonstrated by integrated systems. Integration of PV cells and supercapacitors becomes a new strategy to boost device performance, especially in terms of conversion efficiency and storage capacity, as innovations in these technologies are still aggressively studied. To guarantee utility as both an energy generator and storage system, a well-considered integrated device architecture is suggested. The integration of pertinent materials and the difficulties encountered during device manufacturing are addressed in this article, therefore supporting a new and affordable technology. Gaps in the research are found, and advice for additional studies follows.

Supercapacitors

Commonly known as ultracapacitors or electrochemical capacitors, supercapacitors are a special type of energy storage devices lying between batteries and regular capacitors. Unlike batteries, which use chemical processes to store electricity, supercapacitors store it by mechanistically separating charges at the interface of their electrodes and electrolyte. Supercapacitors can reach amazing power densities with quick charge and discharge rates thanks to this mechanism, making them especially fit for applications requiring quick energy supply. A supercapacitor can produce power levels that are up to one hundred times greater than those of batteries of equivalent volume, although its energy storage capacity is generally 3 to 30 times less. Therefore, supercapacitors are particularly advantageous in scenarios requiring significant power output over brief durations, such as during energy surges, without necessitating extensive energy storage. Conventional capacitors, irrespective of whether they are electrostatic or electrolytic, store charge on plates that typically have a limited surface area. In contrast, supercapacitors achieve charge storage through either an electric double layer formed by ions or via rapid redox reactions at the junction between an electrode with high specific surface area and a liquid electrolyte (Lechêne et al., 2016). The distinctive electrode design of a supercapacitor—usually made of porous materials offering a great surface area—defines its main property. Activated carbon, carbon nanotubes, and graphene are among typical electrode materials as they provide great surface area for charge storage and increase charge transfer efficiency. Serving as the medium for ionic transit between the electrodes, usually made up of an aqueous or organic solution containing ions, the electrolyte enables the processes of energy storage and discharge. Supercapacitors' operational concepts and characteristics inside energy storage applications have been made clear by Özada and colleagues.

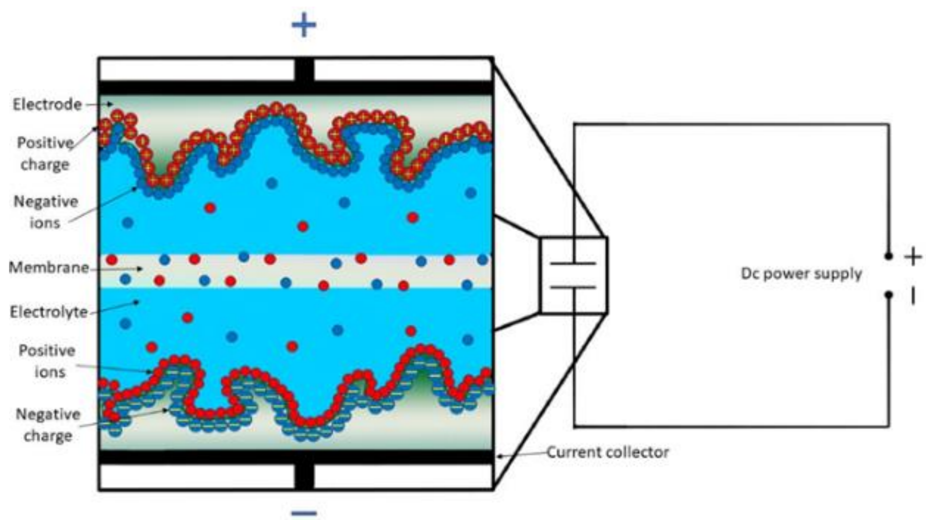


Figure 1: Basic Structure of Supercapacitor (Czagany et al, 2024)

Supercapacitors are mostly divided into two basic types depending on the materials employed for their electrodes and their electrolyte composition: pseudocapacitors and electrochemical double-layer capacitors (EDLCs). Using the creation of an electric double layer, EDLCs mainly store energy by the physical adsorption of ions at the intersection between the electrode and electrolyte. On the surface of the electrode, pseudo capacitors, by contrast, go additional electrochemical redox processes that increase their energy storage capacity beyond that of EDLCs. Two inert porous electrodes placed in an electrolyte make up an EDLC, with a separator enabling ion mobility. Charge separation inside the electrochemical double layer at the electrode/electrolyte contact (Czagany et al., 2024) allows for energy storage. Additionally, according to their energy storage methods, supercapacitors can be divided into EDLCs, pseudo capacitors also known as redox capacitors, and hybrid capacitors. Figure 2 is a categorization of supercapacitors.

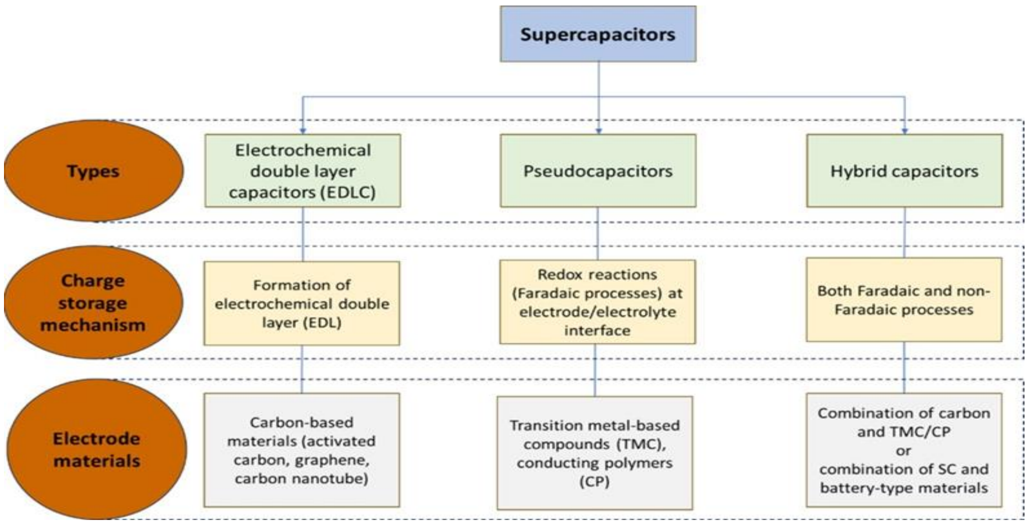


Figure 2: Supercapacitor Categories (Czagany et al, 2024)

The charge separation process in the electrochemical double layer occurs at the boundary between the electrode and electrolyte, with its thickness influenced by several factors such as electrolyte concentration and ion size, typically ranging from 0.5 to 1 nanometer for concentrated electrolytes. Ions necessary for charging the EDLC traverse between the porous electrodes by diffusing through the electrolyte. Hybrid capacitors represent a third category, which amalgamates features from both supercapacitors and batteries by integrating an EDLC electrode with a pseudo capacitive or battery-type electrode. This hybrid configuration is designed to improve the energy density (Ed) of supercapacitors, achieving levels between 20–30 Wh/kg (Czagany et al., 2024). In a hybrid supercapacitor cell, one part operates as an EDLC, while the other functions as a pseudo capacitor or battery. This strategy facilitates the development of supercapacitors that are economical, exhibit high electrical conductivity, mechanical flexibility, and chemical stability. By combining these two electrode types, the shortcomings inherent to each individual electrode can be ameliorated, resulting in higher operational potentials and significantly enhanced specific capacitance, with values typically two to three times greater than those of traditional EDLCs and pseudo capacitors. Hybrid capacitors can be further divided into three distinct subcategories: asymmetric hybrids, battery-type hybrids, and composite hybrid supercapacitors (Czagany et al., 2024).

High power density, quick charging and discharging capability, extended cycle lifespan, and consistent performance across a range of operating situations are among the special benefits of supercapacitors. Optimizing the performance of supercapacitors in a range of energy storage uses—particularly in improving the usefulness and reliability of photovoltaic systems—requires knowledge of their basic processes.

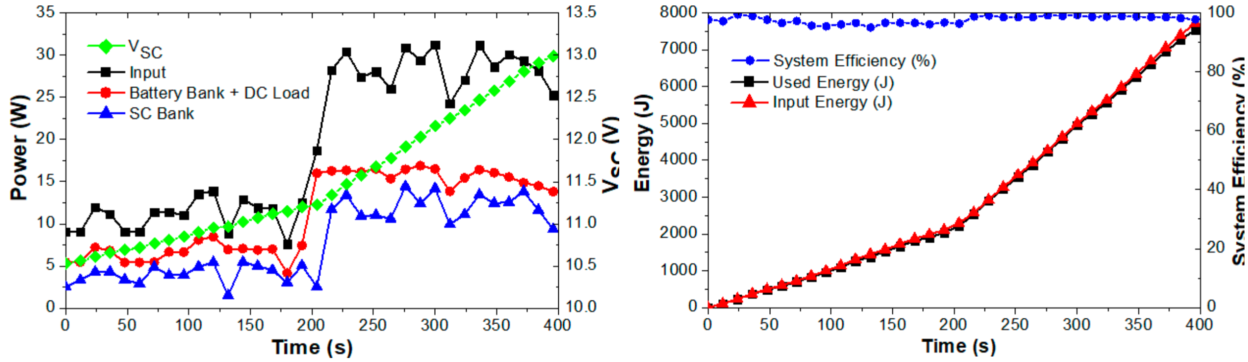
Combined Effect of Supercapacitors in PV System

One practical way to reduce the sporadic character of solar energy and improve general system performance is the inclusion of supercapacitors into photovoltaic (PV) systems. Supercapacitors help PV systems' energy independence and dependability by storing extra energy created during peak solar hours and supplying it at times of low sunshine or rising demand. Several integration techniques exist, including parallel and series layouts with PV panels as well as more general system-level integration employing power electronics and control mechanisms. Supercapacitors capture excess energy from solar panels for later use in parallel configurations together with PV modules. By minimizing grid dependence and maximizing self-consumption of solar energy, this method improves energy management. Supercapacitors also serve as buffering devices that reduce PV output variations brought on by conditions like shadowing, cloud cover, or changes in solar irradiance, hence stabilizing and enhancing system efficiency. (Xu et al, 2016; Liang et al, 2018; Shao et al, 2016; Kiran et al, 2020; Salanne et al, 2016; Hussain et al, 2018; Ibrahim et al, 2021; Shin et al, 2018; Liu et al, 2020).

Integrating super capacitors inside PV systems offers significant benefits for overall system performance, energy storage, and administration. Super capacitors improve the dependability, efficiency, and sustainability of solar energy systems whether deployed in parallel configurations, series arrangements, or integrated with sophisticated control methods, therefore enabling the move toward a renewable energy future by means of great value.

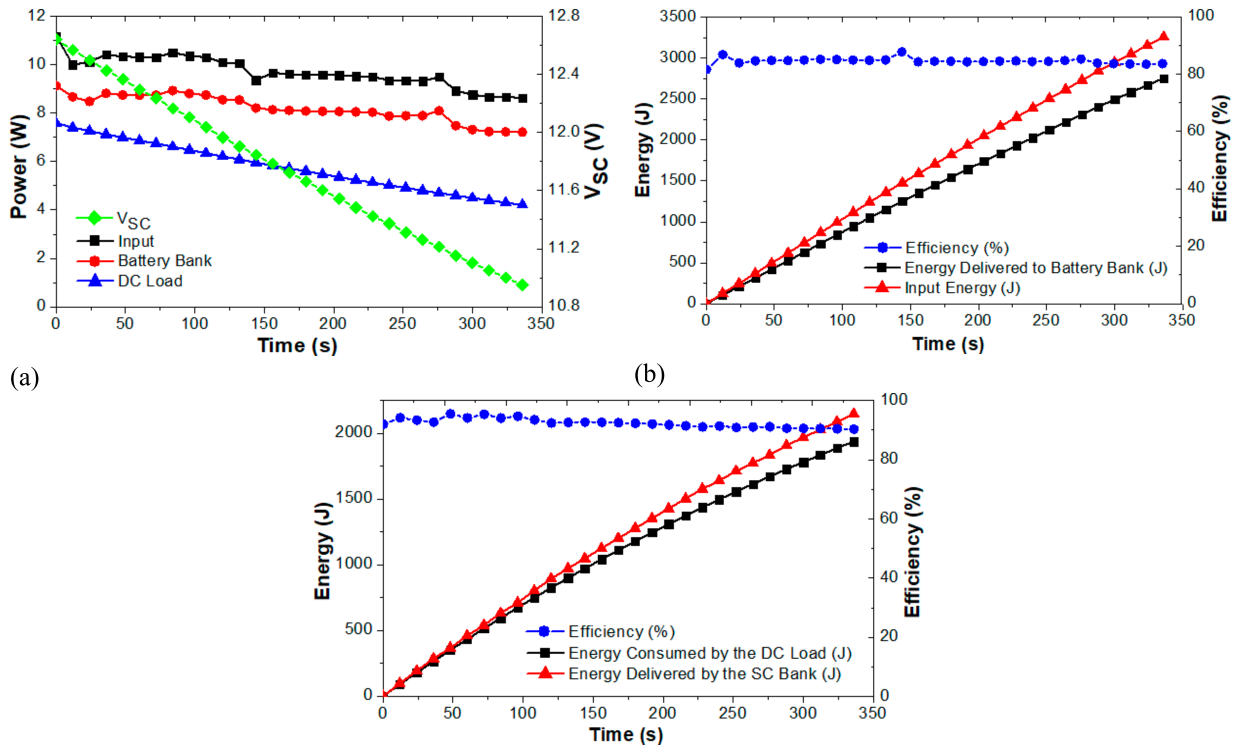
Super capacitors offer various merits that improve system performance, reliability, and efficiency. A significant benefit lies in their rapid charge and discharge capabilities, which facilitate quick responses to fluctuations in solar irradiance and load demands. Their capacity for rapid energy storage and discharge makes them exceptionally appropriate for high-power uses including peak shaving, frequency control, and grid stabilization. Super capacitors also have a long cycle life and provide strong performance under several operating situations. Super capacitors show little deterioration even after many cycles of charging and discharging, unlike conventional batteries, which deteriorate over time as a result of chemical processes and electrode wear. This robustness improves the dependability of energy storage systems while lowering maintenance needs and total lifetime costs. Moreover, super capacitors exhibit greater energy density and efficiency when compared to other storage solutions including batteries. Their great charge/discharge efficiency and little internal resistance help to minimize energy loss during conversions, hence improving the whole system efficiency (Peters et al, 2019; Giannouli et al, 2018; Green et al, 2020; Nakamura et al, 2020; Brahmendra Kumar et al, 2020). Super capacitors can reach greater energy densities, therefore enhancing their storage capacity when combined with cutting-edge electrode materials and electrolytes.

Still, combining super capacitors with PV systems has several difficulties and restrictions that call for management. One major worry is that super capacitors' energy density is comparatively lower than that of batteries, therefore restricting their capacity to store great energy over protracted periods. Developing hybrid energy storage systems combining super capacitors with batteries or other alternative technologies could be imperative to meet the needed energy storage capacity while still maintaining high power density and efficiency (Kumar et al, 2020; Sharma et al, 2021; Zhao et al, 2021; Michael et al, 2020; Kumar et al, 2021; Vicentini et al, 2019). Integration of super capacitors inside photovoltaic systems is also affected by economic considerations. Although super capacitors may save money over time because of their low maintenance and long life, their first costs can surpass those of traditional battery systems. Still, over time, changes in super capacitor technology and economies of scale in manufacturing are expected to reduce these expenses and so improve their financial feasibility. Another difficulty connected to super capacitors is temperature sensitivity since changes in temperature can reduce their lifespan and performance. High temperatures can degrade electrode materials, lower electrolyte conductivity, and so undermine system performance and dependability. Hence, to offset these temperature-related problems and guarantee the best functioning of combined PV and super capacitor systems (Yu et al., 2018; Aziz et al., 2019; Denge, 2016; Takakura et al., 2019; Yang et al., 2019; Zeng et al, 2020), effective thermal management approaches must be implemented. To be clear, super capacitors in PV systems offer significant advantages regarding performance, reliability, and efficiency; nevertheless, it also presents particular problems that need care. Super capacitors can greatly help to make solar energy systems more practical and sustainable by resolving these issues with continuous research, creativity, and technical developments. (Wong et al, 2018; Shi et al, 2018; Lau et al, 2017; Liu et al, 2018; Hart et al, 2019; Qin et al, 2020; Zhang et al, 2021). Driven by growing demand for dependable and effective renewable energy sources, major innovations in the creation and use of super capacitors inside photovoltaic systems have recently appeared. These advancements span materials science, device engineering, system design, and control algorithms—all intended to boost the performance, durability, and cost-effectiveness of PV systems when combined with super capacitors (Wu et al, 2018; Liang et al, 2021; Genovese & Lian, 2017; Makgopa et al, 2019; An et al, 2019). One fascinating path of advancement in super capacitor technology is the development of cutting-edge electrode materials improving electrochemical characteristics and energy storage capabilities. To increase super capacitor's energy density and power density, studies of novel carbon-based materials—such as carbon nanotubes, graphene, and activated carbon composites—as well as transition metal oxides and conducting polymers have been started. These materials enable the creation of especially effective super capacitors for use in photovoltaic energy storage by providing better charge storage capacity, larger specific surface areas, and quicker charge/discharge rates. (Yang et al, 2019; Zeng et al, 2020). See figures 3 and 4 for emphasis.



(a) (b)

Figure 3: Changes In: (A) The Power Supplied By The Photovoltaic (PV) Array, The Amount of power directed to the battery storage and direct current (DC) load, as well as the voltage of the supercapacitor (SC) storage; (B) The energy supplied, energy consumed, and the efficiency of the system plotted against time while the system is functioning in the supercapacitor charging recovery mode (Piyumal Et Al., 2021)



(a) (b)

(c)

Figure 4: Fluctuations In: (A) The Input Power From The Photovoltaic Array, The Energy Supplied To The Battery Bank And The Direct Current Load, As Well As The Voltage Levels Within The Supercapacitor Bank; (B) The Energy Input, The Energy Provided To The Battery Bank, And The Charging Efficiency; (C) The Energy Output From The Supercapacitor Bank, The Power Consumed By The Direct Current Load, And The Efficiency Over Time While The System Operates In Supercapacitor Bypass Mode. (Piyumal Et Al, 2021)

Prospects of Super Cacitor in PV System

Integrating super capacitors inside photovoltaic (PV) systems offers a great chance for invention and progress as demand for renewable energy soars and the need of sustainable energy solutions grows more pressing. Looking ahead, multiple crucial domains come to light for the future research, development, and application of synergic photovoltaic and super capacitor systems (Baena-Moncada et al., 2021; Sun & Yan, 2017; Brahmendra Kumar et al. & Li et al., 2021). The ongoing development of super capacitor technology is given major focus to raise overall efficiency, power density, and energy density. Along with retaining their quick charge and discharge capabilities and extended cycle lifetime, contemporary research is centered on discovering new electrode materials, electrolytes, and device designs that might improve super capacitors' energy storage capacity and operational performance. Progress in nanomaterial, hybrid energy storage solutions, and manufacturing methods show promise for making significant advances in super capacitor cost-effectiveness and efficiency.

The cooperation between super capacitors and new PV technologies—including perovskite solar cells, tandem solar cells, and organic photovoltaics (Luo et al., 2017)—is another important focus area. These new PV technologies provide the promise of improved efficiencies, cheaper production costs, and more flexibility in comparison with traditional silicon-based solar cells, therefore opening up new opportunities for the integration of PV and super capacitor systems over a range of applications. Researchers hope to create affordable, light-weight, and effective solutions for distributed energy generation, grid connectivity, and electrification projects by fusing the benefits of cutting-edge PV technologies with the energy storage advantages of super capacitors.

Beyond technical developments, next studies will tackle major obstacles and obstacles impeding the broad use of integrated PV and super capacitor systems. Factors pertaining to cost competitiveness, scalability, standardization, and regulatory compliance will command focus (Sun & Yan, 2017). Overcoming these obstacles and hastening the worldwide deployment of integrated PV and super capacitor systems will depend on cooperative research projects including academia, business, and government entities.

Moreover, enhancing the operation and performance of integrated PV and super capacitor systems will depend on the development of complex control algorithms and energy management techniques. Using real-time data, predictive analysis, and machine learning methods, scientists can develop clever control systems that reduce grid effects, maximize energy capture, and enhance storage. Under different operating circumstances and grid environments, these sophisticated control approaches would let integrated PV and supercapacitor systems run independently, flexibly, and effectively (Xu et al., 2016; Liang et al., 2018; Shao et al., 2016; Kiran et al., 2020 & Salanne et al., 2016).

Integration of super capacitors inside PV systems shows great potential for influencing the direction of renewable energy and supporting the move towards a sustainable energy system. By stressing technological advancement, encouraging research collaborations, and championing supportive policies, stakeholders may discover new possibilities and overcome the problems presented by the widespread use of integrated PV and supercapacitor systems, therefore helping to create a more sustainable, resilient energy future. (Peters et al., 2019; Giannouli et al., 2018; Green et al., 2020; Nakamura et al., 2020 & Brahmendra Kumar et al., 2020).

Electrode Materials for Super Capacitors

Because of their high specific surface area and excellent electrical conductivity, carbon-based materials—specifically carbon nanotubes (CNTs), graphenes, and MXenes—are often used as electrodes in super capacitors. Usually, CNTs have tensile strength of 100–200 GPa, electrical conductivity of roughly 10^7 S/m, and thermal conductivity near 2000 W/m•K. An earlier study created an all-solid-state integrated gadget using free-standing and aligned films of carbon nanotubes, which showed a general photoelectric conversion efficiency and energy storage efficiency of almost 6.3%, attributing this performance to the structured alignment and great electronic characteristics of the CNT film electrode. Furthermore, the device's adaptability makes it extremely appropriate for a range of applications especially in portable electronic devices (Nakamura et al., 2020). Another interesting outcome was observed when a dye-sensitized solar cell (DSSC) was coupled with a supercapacitor using a CNT film as the common electrode to provide a power conversion efficiency (PCE) of 7.0%, a specific capacitance of 48 F/g, and a storage efficiency approaching 78%. Achieving overall photoelectric conversion and storage efficiencies around 6.3%, the resulting system is lightweight and flexible. Conversely, graphene is created by several ways including chemical vapor deposition, chemical synthesis, microwave synthesis, and mechanical and chemical exfoliation. With its great specific surface area, graphene shows improved ability for electrostatic charge storage, hence making it ideal for supercapacitor electrode uses. Though it is still a somewhat novel material, graphene has been the center of much study into its incorporation in energy storage and solar cell systems. A DSSC using a compact mesoporous titania (TiO_2) film as the anode was successfully combined with a symmetrical supercapacitor utilizing polypyrrole/reduced graphene oxide (PPy/rGO) electrodes for the counter electrode, resulting in a supercapacitor specific capacitance of 308.1 F/g and a projected DSSC PCE of 3.3%. After 51 charge/discharge cycles, the integrated device showed a specific capacitance of 134.7 F/g and a charge retention percentage of 74.8%. Furthermore attracting a great deal of research interest for their potential in supercapacitor electrodes, MXenes are developing as a new class of material. One illustration of this integration of a flexible organic photovoltaic cell with a $Ti_3C_2T_x$ MXene electrode and an organic ionogel electrolyte is achieving a remarkable power conversion efficiency of 13.6% along with a volumetric capacitance of 502 F/cm³. With this simple manufacturing method, the storage efficiency was an outstanding 92%. Using an MXene/black phosphorus (BP)-based supercapacitor combined with a solar cell (Brahmendra Kumar et al., 2020), another relevant study created wearable electronics. The resulting MXene/BP-based microsupercapacitor showed an astonishing specific capacitance of 924.78 F/cm³ and an excellent rate performance of 251.2 F/cm³, along with sturdy long-term cycling stability of 94.23% across thousands of cycles.

CONCLUSION

Including supercapacitors in photovoltaic (PV) systems provides a good approach to solve the energy storage problems related to solar energy and so speeds the move toward a sustainable energy model. Supercapacitors are perfect for uses needing dependable and efficient energy storage solutions since they provide several clear advantages including great power density, quick charge and discharge rates, and a long cycle life. Scholarly literature on the contributions of supercapacitors to PV energy systems has seen a dramatic rise in recent years. Experimental findings suggest that the system experiences reduced efficiencies when operating in neutral mode; however, it achieves enhanced efficiency in supercapacitor charge recovery mode, surpassing existing commercial PV systems. This means that like a typical standalone PV arrangement, the direct link of the PV array to the charge controller causes a decrease in average efficiency when the system runs in SC bypass mode. Eventually, we anticipate that the understanding acquired from this study will quickly become generally accessible for business uses in the photovoltaic sector.

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