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Review

Harnessing Solar Power: A Review of Photovoltaic Innovations, Solar Thermal Systems, and the Dawn of Energy Storage Solutions

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Abstract: The goal of this review is to offer an all-encompassing evaluation of an integrated solar energy system within the framework of solar energy utilization. This holistic assessment encompasses photovoltaic technologies, solar thermal systems, and energy storage solutions, providing a comprehensive understanding of their interplay and significance. It emphasizes the importance of solar energy as a renewable resource and its role in addressing global energy demand and mitigating climate change. The review highlights the significance of advancements in various solar energy technologies, focusing on their environmental benefits, including greenhouse gas emissions reduction and air and water pollution mitigation. It explores the evolution of photovoltaic technologies, categorizing them into first-, second-, and third-generation photovoltaic cells, and discusses the applications of solar thermal systems such as water heaters, air heaters, and concentrators. The paper examines key advancements in energy storage solutions for solar energy, including battery-based systems, pumped hydro storage, thermal storage, and emerging technologies. It references recent published literature to present findings on energy payback time, carbon footprint, and performance metrics. Challenges to widespread adoption are discussed, including cost and economic viability, intermittency, environmental impacts, and grid integration. Strategies to overcome these challenges, such as cost reduction, policy support, energy storage integration, and sustainable practices, are presented based on published literature. By bridging gaps in existing literature, this comprehensive resource aims to equip researchers, policymakers, and industry professionals with insights into forging a sustainable and renewable energy future.

Keywords: renewable energy; solar energy; PV technology; energy storage; greenhouse gas emissions; sustainable development

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1. Introduction

In recent times, the world has become acutely aware of the pressing need to transition away from conventional energy sources like fossil fuels due to their harmful environmental consequences. The ongoing changes in climate patterns, rising global temperatures, and the depletion of finite fossil fuel reserves have necessitated a shift towards more sustainable alternatives. Among these alternatives, solar energy stands out as a beacon of hope [1]. Solar energy is harnessed through the capture and utilization of the sun's radiant light and heat. This form of energy is not only abundant, as the sun radiates an immense amount of energy every day, but is also renewable, meaning it can be continuously replenished [2]. Unlike fossil fuels, which take millions of years to form and are finite in supply, solar energy is essentially limitless and can be harnessed as long as the sun continues to shine [3].

One of the most compelling advantages of solar energy lies in its potential to significantly reduce greenhouse gas emissions [4]. Traditional methods of energy production, such as burning coal, oil, and natural gas, release vast amounts of carbon dioxide and other pollutants into the atmosphere. These emissions are a major contributor to global warming and the detrimental effects associated with it. Solar energy, on the other hand, generates electricity without emitting greenhouse gases during its operation. As governments, industries, and individuals around the world recognize the urgent need for sustainable energy solutions, solar power has emerged as a promising answer. Its potential to address the challenges of climate change, reduce reliance on finite fossil fuels, and create a cleaner, more resilient energy infrastructure positions solar energy as a pivotal player in shaping a more sustainable and prosperous future for the planet.

A comprehensive solar energy system draws upon the synergy of three key components: photovoltaic (PV) technologies, solar thermal systems, and energy storage solutions. In recent years, significant advancements have been made in these three components, revolutionizing the efficiency, scalability, and reliability of solar energy systems. These breakthroughs have propelled solar energy to the forefront of the global energy landscape, with the potential to reshape how we generate, store, and utilize power. The importance of these innovations cannot be overstated. PV technologies have undergone rapid advancements, enhancing solar cell efficiency, reducing manufacturing costs, and increasing their applicability in various environments [5,6]. These developments have opened up new avenues for large-scale solar power generation and enabled the integration of solar energy into our everyday lives [7]. Similarly, advancements in solar thermal systems have expanded their capacity to capture and convert solar heat into usable energy. These systems have demonstrated remarkable efficiency gains, making them increasingly viable for industrial processes, space heating, and electricity generation. The integration of solar thermal systems with existing infrastructure holds the potential to transform industries and reduce reliance on conventional energy sources [8]. Furthermore, the emergence of efficient energy storage solutions has addressed one of the biggest challenges associated with solar energy utilization—its intermittent nature [9]. The development of cost-effective and scalable energy storage technologies has revolutionized the solar energy landscape, enabling the deployment of reliable and dispatchable power systems. Energy storage solutions not only facilitate the integration of solar energy into existing grids but also promote grid resilience and demand management and enable off-grid applications. Thus, the motivation for conducting this study lies in the remarkable and rapid advancements that have taken place in the realm of solar energy technologies, particularly in PV systems, solar thermal technology, and energy storage solutions. These advancements have brought about transformative improvements in the efficiency, scalability, and reliability of solar energy systems, positioning them as a key driver in reshaping the global energy landscape.

The landscape of solar energy research and literature has witnessed the exploration of various facets of solar technologies through a multitude of review papers. These papers have been instrumental in shedding light on the significance and potential of solar energy, yet a notable gap persists—a comprehensive review that unifies the latest advancements in PV technologies, solar thermal systems, and energy storage solutions. While individual review papers have focused on specific technologies or aspects of solar energy, a comprehensive synthesis of the latest innovations and their implications is essential to provide a holistic understanding of progress in solar energy utilization. Some review papers have focused on the development of PV technologies and their efficiency improvements [10–13]. Others have examined advancements in solar thermal systems and their potential applications in various industries [8,14–16]. Additionally, there are review papers that have explored the role of energy storage solutions in enhancing the integration of solar energy into existing grids and promoting renewable energy deployment [17–20]. However, the compartmentalized nature of these reviews has inadvertently omitted a crucial perspective—the interplay, synergies, and integration potential of these distinct solar technologies. The necessity of a comprehensive review emerges from the recognition that solar energy systems are not solitary entities, but rather intricate interconnections of PV systems, solar thermal setups, and energy storage configurations. By overlooking the interdisciplinary nature of these technologies, the existing review papers limit our comprehension of their collective impact and the possibilities they jointly offer. To bridge this scholarly gap, a comprehensive review is imperative—one that transcends the confines of individual technology silos and embraces a holistic approach. Such a review would unravel the intricate relationships between PV technologies, solar thermal innovations, and energy storage advancements. It would uncover how their convergence can lead to the creation of exceptionally efficient and sustainable solar energy systems, capable of addressing the challenges of intermittent supply, enhancing energy yield, and elevating overall system performance.

This review paper aims to fill this gap in the literature by providing a comprehensive analysis of the latest advancements in PV technologies, solar thermal systems, and energy storage solutions. The primary objectives of this review paper include providing an in-depth analysis of the significant strides made in PV technologies. Specifically, it aims to elucidate how these advancements have led to enhanced solar cell efficiency, reduction in manufacturing costs, and broader applicability across diverse environments. Another key objective is to investigate the recent progress in solar thermal systems and their increased capacity to capture and convert solar heat into usable energy. The paper intends to shed light on the remarkable gains in efficiency that solar thermal systems have achieved, making them increasingly viable for critical applications such as industrial processes, space heating, and electricity generation. Finally, a significant focus of the study is directed towards the emergence of efficient energy storage solutions. The paper aims to explore how these solutions have addressed one of the most significant challenges associated with solar energy—its intermittent nature. By examining the development of cost-effective and scalable energy storage technologies, the study seeks to illuminate how these innovations have revolutionized the solar energy sector. In essence, this review paper aims to provide a comprehensive and up-to-date overview of recent advancements in PV technologies, solar thermal systems, and energy storage solutions. By highlighting their significance and potential, the study intends to contribute to a deeper understanding of how solar energy is rapidly transforming the global energy landscape and offering novel pathways towards a sustainable, reliable, and cleaner energy future.

2. Photovoltaic Innovations

PV technology is a cornerstone of solar energy conversion, enabling the direct conversion of sunlight into electrical energy [21]. PV systems consist of solar panels composed of interconnected solar cells, which are the fundamental building blocks responsible for converting light energy into electricity. The operation of PV cells relies on the PV effect, a phenomenon discovered in the 19th century [22]. When photons from sunlight strike the surface of a PV cell, they transfer their energy to the atoms within the cell's semiconductor material, causing the release of electrons. These free electrons generate an electric current as they flow through the cell, creating usable electrical energy. Figure 1 shows how a typical PV cell works and generates electricity. The following subsections describe PV technology in detail.

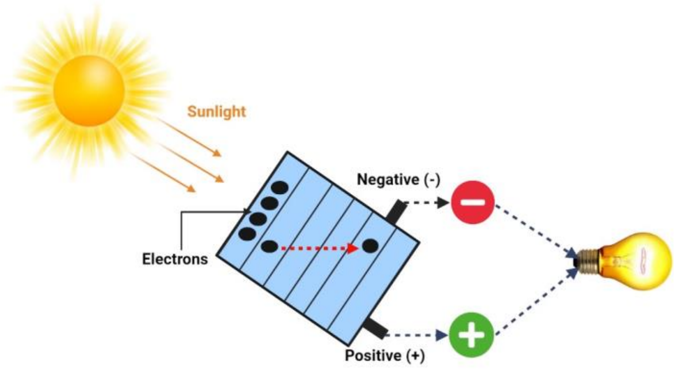

Figure 1. The working principles of a typical PV cell.

2.1. Evolution of PV Technologies

The evolution of PV technologies can be classified into three generations based on the materials used, production methods, and aims to address various challenges and opportunities within the evolving landscape of solar energy [23]. The first generation of PV cells, characterized by their use of crystalline silicon as the primary material, established the foundation of solar energy conversion. The second generation introduced thin-film technologies, incorporating materials like amorphous silicon, cadmium telluride, and copper indium gallium selenide. The third generation encompasses emerging technologies, such as organic and dye-sensitized solar cells, aiming to enhance efficiency, lower manufacturing costs, and introduce novel form factors.

- First-generation PV cells: First-generation PV cells, predominantly based on crystalline silicon, marked the early stage of PV technology development. Crystalline silicon cells, either monocrystalline or polycrystalline, exhibited relatively high energy conversion efficiencies but involved expensive manufacturing processes and required thick silicon wafers [24]. These cells served as the foundation for the growth of the PV industry and set the stage for subsequent advancements. Crystalline silicon-based PV cells have been extensively studied and optimized over the years. According to a study by Saga et al. [25], the efficiency of commercial monocrystalline silicon cells has improved from around 10% in the early 1980s to over 25% in recent years. The study also highlighted advancements in manufacturing techniques, such as diamond-wire sawing, which have led to a reduction in material waste and lower manufacturing costs. Numerous researchers have undertaken efforts to enhance the efficiency of monocrystalline silicon cells. One such approach involves employing passivated emitter rear contact (PERC) technology. This technique entails passivating the rear surface of the solar cell to reduce the recombination of charge carriers and improve overall efficiency. This approach enhances light capture and helps achieve higher conversion efficiency [26,27]. Another avenue of advancement is the utilization of bifacial solar cells. These specialized cells can capture sunlight from both the front and rear sides, utilizing reflected and diffuse light from surrounding surfaces. This can lead to increased energy production and higher efficiencies [28]. Additionally, researchers like Uzu et al. [29] used multi-junction solar cells by stacking multiple layers of different semiconductor materials on top of each other. Each layer absorbed a different portion of the solar spectrum, increasing the overall efficiency of light absorption and energy conversion.
- Second-generation PV cells: The evolution of PV technologies led to the emergence of second-generation PV cells, primarily represented by thin-film technologies. Thin-film PV cells offer advantages such as lower material costs, flexibility, and the potential for large-scale production [30]. One notable thin-film technology is cadmium telluride (CdTe) solar cells. A study by Dharmadasa et al. [31] highlighted that CdTe thin-film solar cells have achieved high conversion efficiencies, reaching a record efficiency of 22.1%. The study emphasized the potential of CdTe technology in commercial-scale applications due to its low manufacturing costs and high

performance under real-world conditions. Another significant second-generation thin-film technology is copper indium gallium selenide (CIGS) solar cells. A study by Nakamura et al. [32] demonstrated a record efficiency of 23.35% for CIGS thin-film solar cells. The study highlighted the potential of CIGS technology for high-efficiency, low-cost, and lightweight solar cells, making them suitable for various applications, including building-integrated photovoltaics.

- Third-generation PV cells: Third-generation PV cells encompass a range of emerging technologies that aim to further enhance the efficiency and capabilities of solar energy conversion. Perovskite solar cells have gained significant attention due to their potential for high efficiency and low-cost production. A study by Yoo et al. [33] reported a perovskite solar cell with a certified efficiency of 25.2%. The study highlighted the rapid advancements in perovskite solar cells and their potential for commercialization, although challenges such as stability and scalability still need to be addressed. Another emerging technology in third-generation PV cells is tandem solar cells. Tandem solar cells combine different semiconductor materials with complementary absorption properties to achieve higher conversion efficiencies. A study by Al-Ashouri et al. [34] demonstrated a record efficiency of 29.15% for a four-terminal perovskite/silicon tandem solar cell. The study emphasized the potential of tandem solar cells to exceed the efficiency limits of single-junction cells and pave the way for even more efficient PV systems. Organic solar cells are also third-generation PV cells; they are widely studied in academia and much effort has been invested to commercialize this technology. These cells are also known as organic photovoltaics (OPVs). OPVs utilize organic materials as the active semiconductor layer to convert sunlight into electricity. These cells offer flexibility and the potential for low-cost manufacturing [35]. Despite lower efficiencies compared with traditional silicon-based cells, recent advancements have pushed reported efficiencies beyond 18% [36]. An example of such progress is work by Cai et al. [37], which demonstrated a power conversion efficiency of 18.6% using two compatible non-fullerene acceptors. This showcases the growing potential of OPVs as a lightweight, flexible, and adaptable solar energy solution within the evolving PV landscape.

These studies demonstrate the continuous advancements in PV technologies across different generations. While first-generation PV cells based on crystalline silicon remain highly efficient and stable, second-generation thin-film technologies such as CdTe and CIGS offer advantages in terms of cost effectiveness and flexibility. Third-generation PV cells, including perovskite and tandem solar cells, hold great promise for achieving higher efficiencies and pushing the boundaries of solar energy conversion. These examples highlight the ongoing research and development efforts in the field of PV technologies, driving innovation and paving the way for more efficient and economically viable solar energy systems.

2.2. Key Advancements in PV Technologies

- Efficiency improvements: Efficiency improvements have been a focal point in the advancement of PV technologies, aiming to maximize the conversion of sunlight into electricity. Significant progress has been made in enhancing the efficiency of PV cells through various approaches. One notable advancement is the development of passivation techniques to minimize energy losses at the cell's surface. For instance, the implementation of atomic layer deposition (ALD) for passivation layers has demonstrated notable improvements in the conversion efficiency of crystalline silicon solar cells [38]. A study by Hallam et al. [39] reported a significant enhancement in the performance of silicon solar cells through the application of ALD passivation layers, resulting in a 0.7% absolute efficiency gain. Additionally, the utilization of multi-junction solar cells has contributed to efficiency improvements. Multi-junction cells, composed of multiple semiconductor layers with different bandgaps, can capture a broader spectrum of sunlight and convert it into electricity [40]. A study by Geisg et al. [41]

demonstrated a record efficiency of 47.1% for a four-junction solar cell, highlighting the potential of multi-junction designs in achieving higher conversion efficiencies.

- Cost reduction strategies: Reducing the cost of PV systems is crucial for their widespread adoption and competitiveness in the energy market. Various strategies have been employed to achieve cost reductions in PV technologies. One important advancement is the use of innovative manufacturing processes. For example, roll-to-roll (R2R) manufacturing techniques have been introduced for the production of thin-film PV cells. R2R processes enable high-volume, continuous production with reduced material waste and lower manufacturing costs [42]. A study by Peng et al. [43] highlighted the potential of R2R techniques for the large-scale production of organic solar cells, offering cost advantages and scalability. Furthermore, advancements in material choices have contributed to cost reductions. For instance, the development of non-toxic and abundant materials, such as perovskites, has shown promise for low-cost PV applications. Perovskite solar cells offer the advantage of solution processability, enabling efficient and cost-effective manufacturing. A study by Cao et al. [44] demonstrated a certified efficiency of 25.2% for perovskite solar cells using earth-abundant tin-based perovskite materials, highlighting their potential for low-cost PV technologies.
- Novel materials and manufacturing techniques: The exploration of novel materials and manufacturing techniques has been instrumental in advancing PV technologies and expanding their capabilities. One notable advancement in materials is the integration of nanomaterials into PV cells. Nanomaterials, such as quantum dots and nanowires, offer unique properties that can enhance light absorption and charge transport in PV devices [45]. A study by Maraghechi et al. [46] demonstrated the use of colloidal quantum dots to enhance the absorption range and efficiency of solar cells, highlighting the potential of nanomaterials for improving PV performance. Moreover, advancements in manufacturing techniques have contributed to the scalability and cost effectiveness of PV technologies. One such advancement is the development of printing technologies for PV cell fabrication. Printing techniques, such as screen printing and inkjet printing, enable high-throughput and low-cost production of PV devices. A study by Pendyala et al. [47] demonstrated the use of inkjet printing for fabricating perovskite solar cells, showing the potential for large-scale manufacturing with high precision and efficiency.

These advancements in PV technologies, including efficiency improvements, cost reduction strategies, and the utilization of novel materials and manufacturing techniques, are driving the progress and commercialization of solar energy. By continuously pushing the boundaries of performance, scalability, and affordability, PV technologies are becoming increasingly competitive and viable for widespread adoption in the global energy landscape. A summary of the findings obtained by various researchers using different types of PV cells is presented in Table 1.

Table 1. A summary of the findings obtained by various researchers using different types of PV cells.

Sources	Type of PV Cell	Output Efficiency	Main Findings
Saga et al. [25]	Monocrystalline	>25%	Improved efficiency and reduced manufacturing costs through diamond-wire sawing.
Dharmadasa et al. [31]	CdTe Thin-film	22.1%	High conversion efficiency and low manufacturing costs for commercial-scale applications.
Nakamura et al. [32]	Copper Indium Gallium Selenide (CIGS)	23.35%	High-efficiency, low-cost, and lightweight solar cells suitable for various applications.
Yoo et al. [33]	Perovskite	25.2%	Rapid advancements in perovskite solar cells with commercialization potential.

Table 1. *Cont.*

Sources	Type of PV Cell	Output Efficiency	Main Findings
Al-Ashouri et al. [34]	Tandem	29.15%	Four-terminal perovskite/silicon tandem solar cell with high conversion efficiency.
Hallam et al. [39]	Silicon	25.7%	ALD passivation layers enhance silicon solar cell performance.
Geisg et al. [41]	Multi-junction	47.1%	Four-junction solar cell with high conversion efficiency.
Cao et al. [44]	Perovskite	25.2%	Earth-abundant tin-based perovskite materials for low-cost PV technologies.
Ansari et al. [48]	Gallium Arsenide	28.3%	Gallium arsenide solar cells with potential for high conversion efficiency.
Morales-Acevedo et al. [49]	Dye-sensitized	11.3%	Enhanced efficiency and stability of dye-sensitized solar cells using improved materials.
Liu et al. [50]	Organic–Inorganic Hybrid	11%	Enhanced efficiency and thermal stability of organic–inorganic hybrid solar cells.
Zielke et al. [51]	Silicon Heterojunction	17.4%	High-efficiency silicon heterojunction solar cells with reduced recombination losses.
Pandey et al. [52]	Perovskite–Silicon Tandem	30.7%	Record efficiency for perovskite–silicon tandem solar cells, demonstrating great potential.
Pandey et al. [53]	Quantum Dot	12.1%	Quantum dot solar cells with tunable bandgaps for efficient energy conversion.
Sahli et al. [54]	Perovskite–Silicon Tandem	25.2%	Improved performance and stability of perovskite–silicon tandem solar cells.
Ma et al. [55]	Ternary Organic	17.5%	Ternary organic solar cells with enhanced PV performance.
Schmidt-Mende et al. [56]	Dye-sensitized	6.3%	Efficiency improvements and enhanced stability of dye-sensitized solar cells.
Carrillo et al. [57]	Perovskite	20.3%	Lead-free perovskite solar cells with competitive efficiency and stability.
Descoeudres et al. [58]	Silicon Heterojunction	21.38%	Silicon heterojunction solar cells with improved rear-side passivation for higher efficiency.
Philipps et al. [59]	III–V Multijunction	41.6%	High-efficiency III–V multijunction solar cells with potential for space applications.
Sung et al. [60]	Graphene-Based	17.1%	Graphene-based solar cells with enhanced electron transport properties.
Barraud et al. [61]	Silicon Heterojunction	22.1%	Silicon heterojunction solar cells with improved rear passivation and carrier collection.

2.3. Service Life of PV Cells

The service life of PV cells is a critical factor in the sustainability and economic viability of solar energy systems. There are various factors which influence the service life of PV cells, such as material degradation, environmental conditions, and manufacturing processes [62]. Research has been conducted to assess degradation mechanisms and to devise strategies for prolonging the life of PV cells. In a study, Sheikh et al. [63] investigated the degradation of common solar cell materials, such as silicon, cadmium telluride, and copper indium gallium selenide, under high temperatures. The researchers found that temperature cycling between 20 °C and 70 °C accelerated degradation, reducing power conversion efficiency to 4.52% after 10 thermal cycles. Kazem et al. [64] examined the impact of humidity on the performance of PV modules. They observed that prolonged exposure to high humidity led to increased power degradation rates. Specifically, the study reported that increasing humidity from 67.28% to 95.59% dropped efficiency from 13.76% to 9.80%. In another study, Jordan et al. [65] focused on accelerated aging tests to predict the lifetime of PV modules. By subjecting modules to stressors such as temperature cycling and damp heat, the study estimated an average degradation rate of 0.5% per year for commercial PV modules over a 25-year period.

Ongoing research focuses on developing new materials that are more resilient to environmental stressors. Perovskite solar cells, for instance, offer the potential for higher efficiency and improved stability, addressing some of the limitations of traditional silicon-based cells [66]. Enhanced encapsulation techniques can shield PV cells from moisture, oxygen, and UV radiation. Implementing encapsulation with improved barrier properties can significantly extend the service life of PV modules [67]. In addition, improving manufacturing processes and quality control measures can result in more reliable and durable PV cells. Ensuring consistency and minimizing defects during production contribute to longer service lives [68]. Furthermore, designing PV systems with climate-specific considerations can reduce the impact of harsh environmental conditions. By tailoring system components and designs to local climates, the overall longevity of PV cells can be enhanced [69].

3. Solar Thermal Systems

Solar thermal systems harness the heat from sunlight to generate thermal energy, which can be used for various applications. Unlike PV systems that convert sunlight directly into electricity, solar thermal systems focus on capturing and utilizing the sun's heat for heating water, air, or other fluids. This renewable and sustainable form of energy offers significant potential for reducing reliance on fossil fuels and mitigating greenhouse gas emissions [70]. Solar thermal systems find application in a wide range of sectors, including residential, commercial, and industrial settings. Common applications include water heating, space heating, air conditioning, and industrial processes such as drying and desalination [71]. By utilizing solar energy, these systems provide a clean and cost-effective alternative to conventional heating methods, contributing to energy efficiency and environmental sustainability.

3.1. Types of Solar Thermal Systems

3.1.1. Solar Water Heaters

Solar water heaters are one of the most widely adopted solar thermal systems. These systems utilize solar collectors to absorb sunlight and heat a fluid, typically water or a mixture of water and antifreeze, which is then used for domestic hot water needs or space heating [72]. The working mechanism of a typical solar water heater is illustrated in Figure 2.

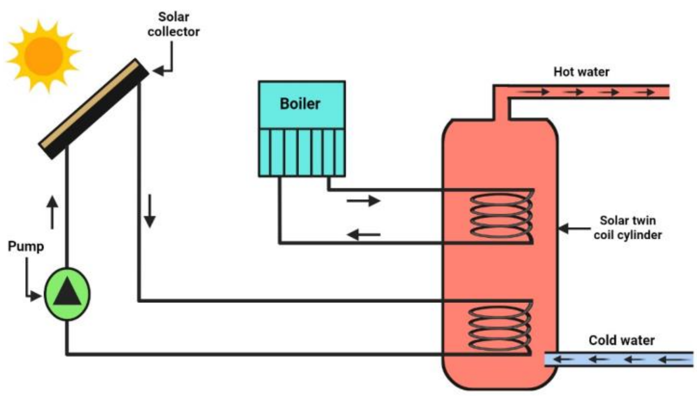

Figure 2. The working mechanism of a typical solar water heater.

Solar water heaters can be categorized into two main types: active and passive systems. In active solar water heaters, pumps or other mechanical means circulate the heated fluid from the solar collector to a storage tank. A study by Mazarrón et al. [73] compared the performance of active solar water heating systems in different climatic conditions. The study found that active systems can achieve higher efficiencies and provide consistent hot water supply, making them suitable for various regions. The results showed that active solar water heating systems achieved efficiencies ranging from 60% to 70%, with higher values observed in regions with ample sunlight.

Passive solar water heaters, on the other hand, rely on natural convection and gravity to circulate the heated fluid. These systems are simpler in design and often used in areas with moderate climates. A study by Ozsoy et al. [74] investigated the performance of a novel passive solar water heating system utilizing a double-glazed flat-plate collector. The study demonstrated the effectiveness of the passive system in providing hot water and highlighted its potential for energy savings and environmental benefits. The passive solar water heating system achieved efficiencies ranging from 50% to 60%, making it a viable option for regions with moderate sunlight.

A study by Elsheniti et al. [75] investigated the performance of a solar water heating system with evacuated tube collectors in a residential building. The study found that the solar water heater system achieved significant energy savings, reducing reliance on conventional energy sources for water heating. The solar water heating system with evacuated tube collectors achieved efficiencies ranging from 65% to 72%, indicating its potential for energy-efficient water heating. In another study by He et al. [76], the performance of a solar water heating system integrated with a heat pump was evaluated. The study demonstrated that the combined system achieved higher energy efficiency and provided consistent hot water supply, even under unfavorable weather conditions. The solar water heating system integrated with a heat pump achieved efficiencies ranging from 70% to 85%, showcasing its capability to enhance energy efficiency and reliability.

3.1.2. Solar Air Heaters

Solar air heaters utilize solar collectors to heat air, which can be used for space heating or drying applications. These systems typically consist of a solar collector, an air circulation system, and a heat storage unit. Figure 3 illustrates the working procedure of a conventional solar air heater. Solar air heaters offer a sustainable and cost-effective solution for space heating in residential and commercial buildings.

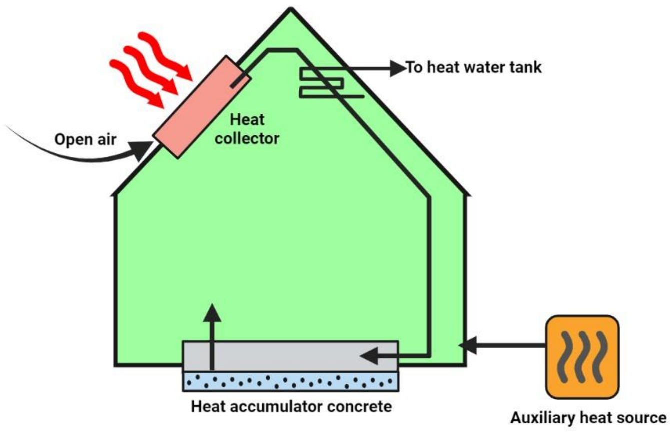

Figure 3. The working procedure of a conventional solar air heater.

A study by Kumar et al. [77] investigated the performance of a solar air heating system with a fin-and-tube heat exchanger. The study analyzed the effects of design parameters on system performance and concluded that the system achieved a thermal efficiency of 60% and provided significant energy savings compared with conventional heating methods. El-Sebaii et al. [78] investigated the performance of a solar air heating system with a double-pass air collector. The study demonstrated that the double-pass configuration increased the system's thermal efficiency to 68% and improved heat transfer, making it suitable for space heating in residential buildings. In another study by Krishnananth et al. [79], the performance of a solar air heater integrated with a heat storage system was evaluated.

The study highlighted the potential of solar air heaters with heat storage for achieving continuous and efficient space heating, achieving a thermal efficiency of 80% and providing stable and reliable heat transfer.

3.1.3. Solar Concentrators

Solar concentrators focus sunlight onto a receiver, generating high temperatures that can be used for power generation or industrial processes. Concentrated solar power (CSP) systems can utilize various configurations, such as parabolic troughs, dish Stirling systems, and solar power towers. The mechanism of concentrating solar energy in a solar power tower solar concentrator is shown in Figure 4.

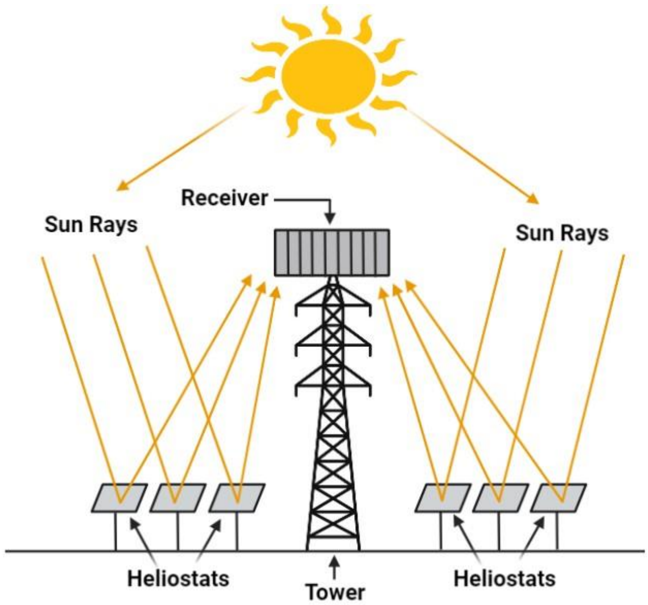

Figure 4. The working mechanism of a solar power tower solar concentrator.

A study by Liu et al. [80] analyzed the performance and economics of a solar power tower system based on a supercritical carbon dioxide (sCO_2) Brayton cycle. The study reported that the sCO_2 power tower system achieved a thermal efficiency of 49.66%, significantly higher than traditional steam-based power tower systems. Additionally, the sCO_2 power tower system demonstrated cost competitiveness, with an estimated levelized cost of electricity (LCOE) of \$0.1046 per kilowatt-hour (kWh), making it a promising option for large-scale solar power generation. Siva et al. [81] reviewed the technological advancements and applications of solar concentrators and power towers for solar thermal power generation. The study highlighted the potential of these systems in achieving high-temperature operation, efficient power conversion, and storage integration. The review highlighted achievements in achieving thermal energy storage at temperatures above 1000 °C, paving the way for continuous and dispatchable solar power generation. Kumar et al. [82] assessed the techno-economic feasibility of solar power tower systems for hydrogen production in India. The study concluded that solar power tower technology showed promise in terms of cost effectiveness and scalability for large-scale hydrogen production. The study reported a LCOE of \$8.23 per kg of hydrogen, demonstrating the cost competitiveness of solar power tower systems in the Indian context.

A Fresnel lens is another type of CSP system that utilizes a stepped structure to mimic the effects of a traditional curved lens while minimizing material usage. This design not only reduces manufacturing costs but also offers unique advantages in solar thermal applications [83]. By focusing sunlight onto a specific target, such as a solar receiver or heat exchanger, Fresnel lenses concentrate solar radiation and elevate temperatures, making them an attractive candidate for various thermal energy applications. Figure 5 illustrates the working procedure of a typical Fresnel lens.

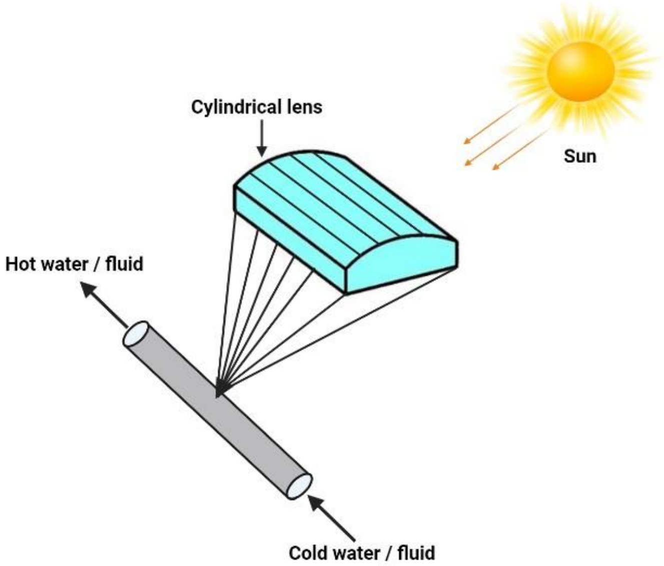

Figure 5. The working procedure of a typical Fresnel lens.

In a study by Pham et al. [84], the performance of a Fresnel-lens-based solar concentrator was evaluated. The study reported a concentration ratio of approximately 576x and an average optical efficiency of 82.4%. The experimental results demonstrate the potential of Fresnel lenses in efficiently concentrating sunlight for solar thermal applications. The researchers Wu et al. [85] investigated the use of Fresnel lenses for solar desalination. The study highlighted that their Fresnel-lens-based system achieved a temperature increase of up to 35 °C, showcasing the ability to generate high thermal energy levels for desalination processes. In another study, Zhai et al. [86] assessed the thermal performance of a Fresnel lens solar collector. Their findings indicated that the collector achieved a maximum temperature of approximately 200 °C, with an average thermal efficiency of 50%. The research underscored the potential of Fresnel lens collectors in achieving elevated temperatures for industrial heating applications.

3.2. Technological Advancements in Solar Thermal Systems

3.2.1. Enhanced Heat Transfer Techniques

Advancements in heat transfer techniques have been crucial in improving the efficiency of solar thermal systems. Researchers have explored various approaches to enhance heat transfer, such as using nanofluids, microchannel heat exchangers, and advanced surface coatings. A study by Wang et al. [87] investigated the application of nanofluids in solar thermal systems. The study demonstrated that the use of nanofluids, which are suspensions of nanoparticles in a base fluid, can significantly improve heat transfer performance, leading to higher system efficiencies. The use of alumina nanofluids in a solar thermal collector enhanced the overall heat transfer coefficient by approximately 18.7% compared with the base fluid. Another approach is the use of microchannel heat exchangers, which offer enhanced heat transfer rates and compact designs. A study by Pu et al. [88] investigated the performance of a solar air heater equipped with microchannel heat exchangers. The study demonstrated improved heat transfer and energy efficiency, highlighting the potential of microchannel heat exchangers for solar air heating applications. The microchannel heat exchanger achieved a heat transfer enhancement of approximately 1.86 times compared with conventional finned-tube heat exchangers. Basbous et al. [89] investigated the application of nanofluids in solar thermal systems to enhance heat transfer. The study demonstrated that the use of copper oxide nanofluids in a solar collector significantly improved the heat transfer coefficient and overall thermal performance. The heat transfer coefficient enhancement with the use of copper oxide nanofluids was approximately 43.5% compared with the base fluid. In another study, Nguyen et al. [90] explored the use of micro-structured surfaces for solar thermal applications. The study demonstrated that micro-structured surfaces could significantly enhance heat transfer by promoting turbulence and increasing the effective surface area for heat exchange. The micro-structured surface heat exchanger achieved a heat transfer enhancement of approximately 42% compared with a smooth-surface heat exchanger.

3.2.2. Advanced Materials for Heat Absorption and Storage

The development of advanced materials has played a significant role in enhancing the performance and efficiency of solar thermal systems. Researchers have explored novel materials for heat absorption, storage, and insulation to improve system effectiveness. One area of focus is the development of selective solar absorbers that can efficiently absorb solar radiation while minimizing thermal losses. A study by Selvakumar et al. [91] investigated the performance of a novel selective solar absorber coating based on carbon nanotubes. The study demonstrated that the carbon-nanotube-based coating exhibited a high solar absorptance of approximately 95% and a low thermal emittance of approximately 10%, enabling efficient solar energy absorption and minimizing thermal radiation losses. Another area of advancement is the development of advanced materials for thermal energy storage. Phase change materials (PCMs) have gained attention for their ability to store thermal energy efficiently. A study by Elsanusi et al. [92] investigated the performance of a solar thermal energy storage system utilizing PCM-based heat exchangers. The study demonstrated that the PCM-based storage system improved overall system efficiency by approximately 25%, reducing energy losses during storage and retrieval. In a similar study, Mazman et al. [93] investigated the use of PCMs in solar thermal systems for thermal energy storage. The study highlighted the potential of PCMs to enhance energy storage capacity, improve system efficiency, and facilitate the utilization of solar energy during non-sunlight hours. The study reported that the incorporation of PCMs in solar thermal systems increased energy storage capacity by approximately 70%. In another study, Liu et al. [94] explored the use of composite materials for solar thermal applications. Their study demonstrated that the incorporation of composite materials, such as carbon-based nanomaterials, in solar absorbers could significantly enhance solar absorption and thermal conductivity. The composite-material-based solar absorber achieved a solar absorbance of approximately 92%.

3.2.3. Integration with Other Energy Systems (e.g., Combined Heat and Power)

Integrating solar thermal systems with other energy systems, such as combined heat and power (CHP) systems, has been explored to maximize the utilization of solar energy and improve overall system efficiency. A study by Razmi et al. [95] investigated the integration of a solar thermal system with a biomass-based CHP system. The study demonstrated that the hybrid system achieved an overall energy conversion efficiency of 78.5%, significantly higher than the individual systems. Solar-thermal-and-biomass-based CHP integration showed potential in enhancing overall energy efficiency and reducing greenhouse gas emissions. Chen et al. [96] explored the integration of solar thermal systems with industrial CHP systems. Their study demonstrated that the integration of solar thermal collectors with CHP units increased overall energy efficiency by approximately 15%. The combined system provided a more reliable and sustainable energy supply for industrial processes. Integration with other renewable energy sources, such as PV systems, has also been explored to optimize energy production and utilization. Corbin et al. [97] investigated the integration of solar thermal collectors with photovoltaic–thermal (PVT) collectors. The hybrid PVT system achieved a thermal efficiency of 66% and an electrical efficiency of 16%, compared with 52% and 14% in standalone systems, respectively. The combined system demonstrated improved energy utilization, making it a promising option for sustainable energy generation. Furthermore, the integration of solar thermal systems with heat pumps has been investigated to improve overall performance and efficiency. A study by Zhou et al. [98] evaluated the performance of a solar thermal and heat pump system for space heating. The hybrid system achieved a coefficient of performance (COP) of 4.9, indicating improved energy efficiency and reduced reliance on conventional heating methods. Table 2 provides an overview of research findings obtained from diverse investigations utilizing various solar thermal systems.

Table 2. An overview of research findings obtained from diverse investigations utilizing various solar thermal systems.

Sources	Type of Solar Thermal System	Output Efficiency	Main Findings
Mazarrón et al. [73]	Active Solar Water Heating Systems	60% to 70%	Active systems achieve higher efficiencies and consistent hot water supply, suitable for various regions.
Ozsoy et al. [74]	Passive Solar Water Heating System	50% to 60%	Passive systems provide hot water with energy savings and environmental benefits, viable for moderate sunlight regions.
Elsheniti et al. [75]	Solar Water Heating System	65% to 72%	Solar water heating systems achieve significant energy savings, reducing reliance on conventional energy sources for water heating.
He et al. [76]	Solar Water Heating System	70% to 85%	Integration with a heat pump achieves higher energy efficiency and a consistent hot water supply, even under unfavorable weather conditions.
Kumar et al. [77]	Solar Air Heating System	60%	A fin-and-tube heat exchanger achieves a thermal efficiency of 60%, with significant energy savings compared with conventional heating methods.
El-Sebaii et al. [78]	Solar Air Heating System	68%	A double-pass air collector increases thermal efficiency and improves heat transfer, suitable for space heating in residential buildings.
Krishnananth et al. [79]	Solar Air Heater	80%	A solar air heater integrated with heat storage achieves continuous and efficient space heating with stable and reliable heat transfer.
Liu et al. [80]	Solar Power Tower System	49.66%	An sCO_2 power tower system achieves higher thermal efficiency and cost competitiveness for large-scale solar power generation.
Siva et al. [81]	Solar Concentrators and Power Towers	N/A	Achievements in thermal energy storage at temperatures above 1000 °C, enabling continuous and dispatchable solar power generation.
Kumar et al. [82]	Solar Power Tower System	\$8.23/kg of H_2	Solar power tower technology shows cost effectiveness and scalability for large-scale hydrogen production in India.
Wang et al. [87]	Nanofluids in Solar Thermal Systems	18.7% enhancement	Nanofluids significantly improve heat transfer performance in solar thermal collectors.
Pu et al. [88]	Microchannel Heat Exchangers	1.86 times	Microchannel heat exchangers improve heat transfer and energy efficiency for solar air heating applications.

Table 2. *Cont.*

Sources	Type of Solar Thermal System	Output Efficiency	Main Findings
Basbous et al. [89]	Nanofluids in Solar Thermal Systems	43.5% enhancement	Copper oxide nanofluids significantly improve the heat transfer coefficient and overall thermal performance in solar collectors.
Nguyen et al. [66]	Micro-structured Surfaces	42% enhancement	Micro-structured surfaces significantly enhance heat transfer by promoting turbulence and increasing the effective surface area for heat exchange.
Selvakumar et al. [91]	Selective Solar Absorber Coating	95% solar absorptance, 10% thermal emittance	Carbon-nanotube-based coating exhibits high solar absorptance and low thermal emittance, enabling efficient solar energy absorption and minimizing thermal radiation losses.
Elsanusi et al. [92]	PCM-based Heat Exchangers	25% efficiency improvement	PCM-based storage improves overall system efficiency and reduces energy losses during storage and retrieval.
Mazman et al. [93]	PCMs in Solar Thermal Systems	70% energy storage increase	PCMs enhance energy storage capacity, improve system efficiency, and facilitate utilization of solar energy during non-sunlight hours.
Liu et al. [94]	Composite Materials in Solar Absorbers	92% solar absorptance	Composite-material-based solar absorbers significantly enhance solar absorption and thermal conductivity.
Razmi et al. [95]	Solar Thermal Biomass-Based CHP	78.5% overall energy conversion efficiency	A hybrid system achieves higher overall energy conversion efficiency and reduces greenhouse gas emissions.
Chen et al. [96]	Solar Thermal Industrial CHP	15% overall energy efficiency increase	Integration of solar thermal collectors with CHP units increases overall energy efficiency and provides a more reliable energy supply for industrial processes.
Corbin et al. [97]	Solar Thermal and PVT Collectors	66% thermal efficiency, 16% electrical efficiency	Hybrid PVT systems demonstrate improved energy utilization and are a promising option for sustainable energy generation

4. Energy Storage Solutions for Solar Energy

The integration of energy storage systems with solar energy plays a vital role in maximizing its utilization and overcoming the intermittent nature of solar power generation. Energy storage technologies enable the capture and storage of excess solar energy during periods of high generation and release it when sunlight is unavailable, thus ensuring a more consistent and reliable power supply. Studies have emphasized the importance of energy storage in enhancing the value and effectiveness of solar energy systems. According to a report by the International Renewable Energy Agency (IRENA), energy storage can increase the self-consumption of solar energy by up to 50% and significantly reduce grid reliance and curtailment of solar power [99].

4.1. Overview of Energy Storage Technologies

4.1.1. Battery-Based Storage Systems

Battery-based storage systems, particularly lithium-ion batteries, have gained significant attention due to their high energy density, efficiency, and cost effectiveness [100]. These systems store excess solar energy in the form of chemical energy and release it as electricity when needed. A study by Vieira et al. [101] evaluated the performance of a lithium-ion battery energy storage system integrated with solar PV installations. The study found that the battery system improved self-consumption of solar energy from 30% to 60% and reduced the reliance on grid electricity. Roberts et al. [102] analyzed the performance of a battery energy storage system (BESS) integrated with a solar PV system. The study found that the BESS increased the self-consumption of solar energy from 30% to over 70%, resulting in a significant reduction in grid electricity purchases. In another study, Qusay et al. [103] evaluated the techno-economic performance of a lithium-ion battery energy storage system for solar self-consumption. The study showed that the battery system improved self-consumption rates by up to 42%, leading to substantial savings in electricity costs.

4.1.2. Pumped Hydro Storage

Pumped hydro storage is a mature and widely deployed energy storage technology. It utilizes the potential energy of water stored at a higher elevation to generate electricity when released downhill during times of high energy demand [104]. This technology provides a large-scale and long-duration storage solution for solar energy. A study by Beevers et al. [105] assessed the potential of pumped hydro storage to support high levels of solar energy penetration in the United States and Europe. The study showed that pumped hydro storage could provide up to 50 GW of flexible capacity, enabling a higher share of solar energy in the electricity mix. Chaudhary et al. [106] investigated the potential of pumped hydro storage for integrating variable solar PV generation. The study showed that pumped hydro storage reduced the curtailment of solar PV energy by up to 50%, enabling higher levels of solar PV penetration into the grid. In another study, Gioutsos et al. [107] evaluated the role of pumped hydro storage in achieving a high share of renewable energy in the electricity system. The study found that pumped hydro storage allowed for a solar energy penetration level of up to 70% and significantly improved system flexibility and stability.

4.1.3. Thermal Storage

Thermal storage technologies store solar energy in the form of heat and release it later for space heating, water heating, or industrial processes. Molten salt storage is a commonly used thermal storage technology, particularly in concentrated solar power (CSP) plants. A study by Boretti et al. [108] evaluated the performance of a thermal energy storage system using molten salt in a CSP plant. The study demonstrated that thermal storage improved the plant's capacity factor by 45%, allowing for continuous power generation even after sunset. Praveen et al. [109] also analyzed the performance of thermal energy storage in CSP plants. The study showed that the inclusion of thermal storage increased the capacity factor of the CSP plant from 37% to 65%, leading to more continuous and reliable power generation. In another study, Liu et al. [110] evaluated the techno-economic performance of a thermal storage system coupled with a solar thermal power plant. The study demonstrated that the integration of thermal storage increased the utilization of solar energy by 40%, resulting in improved system efficiency and economics.

4.1.4. Emerging Storage Technologies

Emerging storage technologies show promise in enabling long-duration and large-scale storage for solar energy. Flow batteries, such as vanadium redox flow batteries (VRFB), offer scalable and flexible storage solutions [111]. Hydrogen storage through electrolysis and fuel cells also presents an avenue for long-duration energy storage [112]. A study by Nguyen et al. [113] investigated the techno-economic feasibility of VRFB systems for solar energy storage. The study demonstrated that VRFB systems could achieve a high round-trip efficiency of 80–90% and provide long-duration storage capabilities. Monforti et al. [114] evaluated the performance of a hydrogen storage system for solar energy integration. The study demonstrated that the hydrogen storage system achieved a round-trip efficiency of 35–40% and provided long-duration storage of up to several weeks. Moreover, Elberry et al. [115] analyzed the potential of hydrogen storage as a seasonal storage option for solar energy in Finland. Their study showed that hydrogen storage systems achieved high energy storage density and long-duration capabilities, enabling storage durations of several months.

4.2. Advances in Energy Storage for Solar Energy

4.2.1. Improvements in Battery Technologies for Solar Applications

Ongoing research and development efforts have focused on improving battery technologies specifically for solar energy storage. This includes advancements in battery chemistries, electrode materials, and system design to enhance energy density, cycle life, and safety. A study by Jia et al. [116] investigated the performance of a lithium-ion battery with a silicon anode for solar energy storage. The study demonstrated that the silicon-anode battery exhibited higher energy density and enhanced cycle life, making it a promising solution for long-lasting and high-capacity solar energy storage. Wessells et al. [117] investigated the performance of advanced lithium-ion batteries for solar energy storage. Their study showed that these batteries achieved a round-trip efficiency of 90% and had a cycle life of over 5000 cycles, indicating their suitability for long-lasting and high-efficiency solar energy storage. In another study, Dong et al. [118] evaluated the performance of lithium iron phosphate (LiFePO4) batteries for solar energy storage. Their study demonstrated that LiFePO4 batteries achieved a round-trip efficiency of 97% and retained 80% of their initial capacity after 5000 cycles, indicating their long cycle life and high durability.

Sodium-based batteries have emerged as promising candidates in the realm of energy storage, offering a potential alternative to traditional lithium-ion batteries. These batteries utilize sodium ions for energy storage, a resource more abundant and less expensive than lithium, thereby addressing some of the supply chain and cost challenges associated with lithium-ion technology [119]. As the renewable energy landscape expands, sodium-based batteries have gained attention for their suitability in stationary storage applications, enhancing grid stability, and enabling efficient utilization of renewable energy sources. Numerous research studies have investigated the performance and potential of sodium-based batteries. For example, Chen et al. [120] explored amorphous $Na_2Ti_3O_7$ as a promising anode material for sodium-ion batteries. The study demonstrated an impressive specific capacity of 96.2 mAh/g at 5 mA/g, emphasizing the potential of this material for high-rate sodium-ion storage. Zhu et al. [121] presented a full sodium-ion battery configuration. The researchers achieved a high energy density of ~410 Wh/kg and excellent capacity retention, showcasing the stability and potential of this sodium-ion cell. In another study, Bai et al. [122] focused on enhancing the rate capability of hard carbon anodes. The researchers achieved a capacity of ~240 mAh/g at a high current density of 25 mA/g, indicating the potential for rapid sodium-ion storage.

4.2.2. Integration of Storage with PV and Solar Thermal Systems

The integration of energy storage systems with solar PV and solar thermal systems has been an area of research to enhance energy management and improve system performance. A study by Jaszczur et al. [123] investigated the integration of a battery energy storage system with a PV system. The study demonstrated that the integration improved the self-consumption of PV energy from 30% to 80%, resulting in increased solar energy utilization and reduced reliance on grid electricity. A similar study was conducted by Appen et al. [124]. Their study showed that the battery system increased self-consumption rates from 34% to 69% and reduced the PV system's reliance on the grid by 50%, demonstrating the effectiveness of storage integration in maximizing solar energy utilization. In the case of solar thermal systems, a study by Boukelia et al. [125] investigated the integration of thermal storage with a solar thermal power plant. The study demonstrated that the integration of thermal storage improved the solar thermal power plant's capacity factor by up to 33%, enabling continuous power generation during periods of low solar radiation.

4.2.3. Grid-Scale Energy Storage Solutions

Advances in energy storage technologies have enabled the development of grid-scale energy storage solutions, facilitating the integration of solar energy into the grid and supporting grid stability. A study by Lu et al. [126] analyzed the potential of grid-scale energy storage for solar energy integration. The study concluded that grid-scale storage, such as pumped hydro storage and batteries, could provide flexibility and enable a higher penetration of solar energy into the grid. Chatzigeorgiou et al. [127] analyzed the performance of a grid-scale BESS integrated with solar PV installations. The study showed that the BESS increased the self-consumption of solar energy from 24% to 80% and reduced the reliance on grid electricity by up to 90%, demonstrating the significant impact of grid-scale storage on solar energy utilization. Moreover, a study by Johnson et al. [128] investigated the benefits of grid-scale energy storage for solar energy integration. The study demonstrated that grid-scale storage increased the solar energy penetration level from 40% to 80% and improved the stability and reliability of the grid. A summary of research findings obtained from a variety of investigations that explore the performance of different solar energy storage systems is tabulated in Table 3.

Table 3. Summary of research findings from diverse solar energy storage systems.

Sources	Type of Energy Storage	Output Efficiency	Main Findings
Vieira et al. [101]	Lithium-ion Battery	30% to 60%	An integrated battery system improved self-consumption of solar energy and reduced reliance on grid electricity.
Roberts et al. [102]	Battery Energy Storage	30% to >70%	BESS increased self-consumption of solar energy, resulting in a significant reduction in grid electricity purchases.
Qusay et al. [103]	Lithium-ion Battery	Up to 42%	A lithium-ion battery system improved self-consumption rates, leading to substantial savings in electricity costs.
Beevers et al. [105]	Pumped Hydro Storage	Up to 50 GW	Pumped hydro storage provided flexible capacity, enabling a higher solar energy share in the electricity mix.
Chaudhary et al. [106]	Pumped Hydro Storage	Up to 50%	Pumped hydro storage reduced curtailment of solar PV energy, enabling higher solar PV penetration into the grid.
Gioutsos et al. [107]	Pumped Hydro Storage	Up to 70%	Pumped hydro storage allowed for up to 70% solar energy penetration, improving system flexibility and stability.
Nguyen et al. [113]	Vanadium Redox Flow Battery	80–90%	VRFB systems achieved high round-trip efficiency and long-duration storage capabilities.
Monforti et al. [114]	Hydrogen Storage	35–40%	A hydrogen storage system achieved significant long-duration storage capabilities with moderate round-trip efficiency.
Elberry et al. [115]	Hydrogen Storage	High storage density and long-duration capabilities	Hydrogen storage systems achieved long-duration storage of several months.
Jia et al. [116]	Lithium-ion Battery with Silicon Anode	Enhanced energy density and cycle life	Silicon anode batteries demonstrated promise for long-lasting and high-capacity solar energy storage.
Wessells et al. [117]	Advanced Lithium-ion Battery	90%	Advanced lithium-ion batteries exhibited high round-trip efficiency and cycle life, suitable for long-lasting storage.

Table 3. *Cont.*

Sources	Type of Energy Storage	Output Efficiency	Main Findings
Dong et al. [118]	Lithium Iron Phosphate Battery	97%	LiFePO4 batteries demonstrated high round-trip efficiency and long cycle life, showcasing high durability.
Jaszczur et al. [123]	Battery Energy Storage	30% to 80%	Integration of a battery system improved PV energy self-consumption, reducing reliance on grid electricity.
Appen et al. [124]	Battery Energy Storage	34% to 69%	Battery integration increased PV system self-consumption and reduced grid reliance, enhancing solar energy utilization.
Boukelia et al. [125]	Thermal Storage	Up to 33%	Thermal storage integration improved solar thermal power plant capacity factor, enabling continuous power generation.
Lu et al. [126]	Grid-scale Storage	Flexible Capacity	Grid-scale storage (pumped hydro and batteries) provided flexibility for higher solar energy penetration into the grid.
Chatzigeorgiou et al. [127]	Grid-scale Battery Energy Storage	24% to 80%	Grid-scale BESS increased self-consumption of solar energy and reduced grid reliance, impacting solar energy utilization.
Johnson et al. [128]	Grid-scale Storage	40% to 80%	Grid-scale storage increased solar energy penetration, improving grid stability and reliability.

4.3. Solar Energy Storage Market Trends

As the renewable energy sector continues to gain momentum, the integration of solar energy storage has emerged as a crucial component in ensuring a sustainable and reliable energy supply. Several key players have risen to prominence in the solar energy storage market, shaping its development and expansion. Tesla, Inc., stands as one of the most recognizable market leaders. Tesla's Powerwall and Powerpack battery storage solutions have become synonymous with residential and commercial solar energy storage [129]. The company's ability to leverage its brand recognition and expertise in battery technology has significantly contributed to the widespread adoption of solar energy storage systems. LG Chem and Samsung SDI have also established themselves as major contributors to the market. Their lithium-ion battery technologies are widely integrated into solar energy storage solutions, offering high energy density, efficiency, and reliability [130]. These companies have invested heavily in research and development to improve battery performance, reduce costs, and enhance overall energy storage capabilities.

Market leaders have effectively differentiated themselves through technological innovations, strategic partnerships, and a focus on user-friendly solutions. Tesla's integration of energy storage with electric vehicle technology has created a synergy between the two sectors. By leveraging their expertise in EV batteries, Tesla has managed to scale up energy storage solutions and capitalize on economies of scale [131]. LG Chem and Samsung SDI have prioritized safety, performance, and customization in their battery offerings. Their batteries can be tailored to fit various applications and scales, providing flexibility for both residential and commercial installations [132]. These companies have also forged collaborations with solar system integrators to provide seamless and integrated solutions to end users.

5. Synergies and Integration

5.1. Synergies between PV Technologies, Solar Thermal Systems, and Energy Storage

Researchers have explored the potential synergies between PV technologies, solar thermal systems, and energy storage to enhance overall system performance, increase energy utilization, and improve system economics. A study by Othman et al. [133] investigated the synergistic combination of PV and solar thermal systems in a hybrid solar energy system. The study showed that the integrated system achieved a solar fraction of up to 86%, demonstrating the synergistic benefits of combining PV and solar thermal technologies for efficient energy conversion and utilization. Furthermore, the integration of energy storage with PV and solar thermal systems has been explored to enhance the self-consumption of solar energy and increase system reliability. For example, Yao et al. (2020) analyzed the synergies between PV, solar thermal, and energy storage systems in a residential microgrid. The study demonstrated that the integrated system achieved a self-sufficiency rate of up to 62.13%, indicating the potential for increased solar energy utilization and reduced reliance on the grid. A similar study was conducted by Astolfi et al. [134] and found an overall energy self-sufficiency rate of 74.9%. In another study, Tercan et al. [135] explored the synergies between PV, solar thermal, and battery energy storage systems. The study showed that the integrated system achieved a self-consumption rate of up to 94.2%, indicating a high level of utilization of solar energy and reduced dependence on the grid. Furthermore, a study by Fachrizal et al. [136] investigated the synergies between PV, solar thermal, and heat storage systems in a multi-energy system. The study demonstrated that the integrated system achieved an energy self-sufficiency rate of 71%, indicating the potential for significant energy autonomy and reduced environmental impact. These studies highlight the synergistic benefits of integrating PV technologies, solar thermal systems, and energy storage. The findings demonstrate the potential for achieving high levels of energy self-sufficiency, increased utilization of solar energy, and reduced dependence on the grid through the integration of these technologies.

5.2. Combined Systems and Hybrid Approaches

Combined systems and hybrid approaches, which involve the integration of different renewable energy technologies, have been explored to maximize energy generation, improve system stability, and enhance energy utilization. A study by Maleki et al. [137] investigated a hybrid system that combines PV, solar thermal, and wind energy. The study showed that the hybrid system achieved a higher energy production of 25.4% compared with individual systems, indicating the synergistic benefits of combining multiple renewable energy technologies. Moreover, hybrid approaches involving the integration of PV and concentrated solar power (CSP) systems have been investigated. A study by Zurita et al. [138] evaluated a hybrid PV–CSP system and showed that the combined system achieved a solar conversion efficiency of up to 43.4%, highlighting the potential for improved solar energy conversion through hybridization. A similar investigation carried out by Han et al. [139] showed that the combined system achieved an overall solar-to-electricity conversion efficiency of 44%, which was higher than the individual PV or CSP systems alone, indicating the synergistic benefits of the hybrid approach. In another study, Wang et al. [140] examined the performance of a hybrid system that combined PV, wind, and hydropower technologies. The study showed that the integrated hybrid system achieved an overall energy self-sufficiency rate of 95%, indicating the high level of energy independence and reliability achieved through the combination of multiple renewable energy sources. Moreover, a study by Tong et al. [141] analyzed a hybrid system that combined PV, solar thermal, and wind technologies. The study demonstrated that the integrated hybrid system achieved a levelized cost of electricity (LCOE) of $0.052/kWh, which was lower than the LCOE of individual standalone systems, highlighting the economic advantages of the hybrid approach.

5.3. Benefits and Challenges of Integrating Multiple Technologies

Integrating multiple renewable energy technologies, such as PV, solar thermal technology, and energy storage systems, offers a range of benefits but also poses certain challenges.

Benefits:

1. Improved energy utilization: Integrating multiple technologies allows for better utilization of renewable energy resources. By combining PV, solar thermal technology, and energy storage systems, overall energy generation and utilization can be optimized, resulting in higher self-consumption rates and reduced dependence on the grid [142].
2. Enhanced system performance: The integration of multiple technologies can lead to improved system performance. Synergistic interactions between different technologies enable more efficient use of energy, higher system efficiency, and better overall performance compared with standalone systems [143].
3. Increased overall efficiency: Integrating multiple technologies can boost the overall efficiency of renewable energy systems. By combining PV, solar thermal technology, and energy storage, the system can achieve higher energy conversion rates, minimize energy losses, and maximize energy output, leading to better energy utilization and reduced waste [144].

Challenges:

1. System complexity: Integrating multiple technologies introduces additional complexity to system design, installation, and operation. It requires careful planning, coordination, and integration of various components and control systems to ensure seamless operation and effective performance [145].
2. Cost: Integrating multiple technologies can involve higher upfront costs compared with standalone systems. The costs associated with integration, including equipment, installation, and control systems, can pose financial challenges, although the long-term benefits and potential savings may outweigh the initial investment [146].
3. Technology compatibility: Integrating different technologies often requires ensuring compatibility and efficient interaction between various components and systems. It may involve addressing technical challenges related to different voltage levels, control interfaces, and operational characteristics, which can present compatibility and interoperability issues [147].

Addressing these challenges and optimizing the integration of multiple technologies can unlock the full potential of renewable energy systems, leading to improved energy utilization, enhanced system performance, and increased overall efficiency. It requires careful planning, technological advancements, and strategic decision-making to achieve successful integration and reap the benefits of combined renewable energy systems.

6. Environmental Sustainability and Impact

6.1. Environmental Benefits of Solar Energy Technologies

Solar energy technologies, such as PV and solar thermal systems, offer significant environmental benefits by reducing greenhouse gas emissions compared with conventional fossil-fuel-based energy sources. A study by Liu et al. [148] assessed the greenhouse gas emissions associated with PV systems. The study found that, over a 30-year period, a PV system with a capacity of 2.4 MW could avoid approximately 32 million metric tons of CO_2 emissions, contributing to greenhouse gas reduction and mitigating climate change. Zhang et al. [149], in one of their studies, estimated that PV systems have a global warming potential of approximately 91.95 g of CO_2 equivalent per kilowatt-hour (gCO_2e/kWh), significantly lower than conventional fossil-fuel-based electricity generation sources.

Solar energy technologies also contribute to the mitigation of air and water pollution compared with conventional energy sources. Studies have demonstrated the environmental benefits of solar energy in terms of reducing emissions of pollutants and improving air and water quality. For example, Granovskii et al. [150] analyzed the life cycle emissions of PV systems. The study showed that emissions of air pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM), associated with PV systems were significantly lower compared with conventional fossil-fuel-based electricity generation. Hertwich et al. [151] conducted a comparative analysis of air pollution-related impacts between PV and fossil-fuel-based electricity generation. The study estimated that, per unit of electricity generated, PV systems have significantly lower emissions of pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM), leading to improved air quality and human health benefits. Additionally, a study by Suresh et al. [152] examined the environmental impact of a solar thermal power plant compared with a conventional coal-fired power plant. The study showed that the solar thermal power plant had significantly lower emissions of air pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury (Hg), leading to improved air quality and reduced health risks.

6.2. Life-Cycle Analysis of Solar Energy Technologies

Life-cycle analysis (LCA) studies provide a comprehensive assessment of the environmental impacts associated with the entire life cycle of solar energy technologies, including PV technologies, solar thermal systems, and energy storage solutions. These studies consider various stages, from raw material extraction and manufacturing to operation, maintenance, and end-of-life management.

LCA studies have focused on assessing the energy payback time (EPBT) and carbon footprint of solar energy technologies to understand their environmental performance. A study by Celic et al. [153] conducted an LCA of different PV technologies. The study reported EPBT values ranging from 1 to 1.5 years, depending on the PV technology and location. The carbon footprint of PV systems was estimated to be around 100–150 g of CO_2 equivalent per kilowatt-hour (gCO_2e/kWh), indicating relatively low emissions compared with conventional electricity generation sources.

LCA studies have also examined the resource consumption and waste generation associated with solar energy technologies, providing insights into their environmental impacts throughout their life cycle. A study by Mahmud et al. [154] conducted an LCA of solar thermal systems, considering various components and their manufacturing processes. The study assessed the resource consumption and waste generation associated with solar thermal collectors, highlighting the importance of optimizing material use and recycling practices to minimize environmental impacts. In terms of energy storage solutions, a study by Yudhistira et al. [155] conducted an LCA of lithium-ion batteries used for energy storage in PV systems. The study assessed the environmental impacts associated with battery manufacturing, use, and end-of-life treatment. It reported that the carbon footprint of lithium-ion batteries ranged from 50 to 140 kg of CO_2 equivalent per kilowatt-hour ($kgCO_2e/kWh$), emphasizing the importance of optimizing battery production and recycling processes.

7. Barriers and Future Prospects

Despite the numerous benefits of and advancements in PV technologies, solar thermal systems, and energy storage solutions, several challenges remain that hinder their widespread adoption. Addressing these challenges is crucial to accelerate the deployment and integration of these technologies into the mainstream energy sector. This section discusses key challenges, potential strategies to overcome them, and future prospects.

1. Cost and economic viability:

Challenge: The initial cost of PV systems, solar thermal systems, and energy storage solutions can be perceived as a barrier for widespread adoption. The upfront investment required for installation and equipment can pose financial challenges, especially in regions with limited financial resources [156].

Strategies to overcome the challenge:

- Continual reduction of costs: Ongoing research and development efforts aim to reduce the cost of PV systems, solar thermal systems, and energy storage technologies. This includes advancements in manufacturing processes, material selection, and system design.
- Government incentives and support: Governments can provide financial incentives, such as subsidies, tax credits, and grants, to promote the adoption of solar energy

technologies and energy storage solutions [157]. These incentives help offset the upfront costs and improve the economic viability of these technologies.

Future prospects: As PV technologies, solar thermal systems, and energy storage solutions continue to advance and economies of scale are achieved through increased production, costs are expected to further decline. Additionally, supportive policies and incentives can encourage wider adoption, making these technologies more economically attractive.

2. Intermittency and grid integration:

Challenge: PV technologies and solar thermal systems are dependent on sunlight availability, leading to intermittency in energy generation. This intermittency poses challenges for integrating these energy sources into the existing power grid, which requires a continuous and reliable power supply [158].

Strategies to overcome the challenge:

- Energy storage integration: Energy storage solutions, such as batteries and pumped hydro storage, can address the intermittency challenge by storing excess energy during periods of high generation and releasing it during low generation periods [159]. A study conducted by Syed et al. [160] highlighted the role of BESS in smoothing out fluctuations in solar generation. BESS can store excess solar energy and release it during periods of reduced generation, thereby providing grid support and maintaining grid frequency stability. Yao et al. [161] proposed an integrated energy management framework that combines distributed energy resources, demand response, and energy storage to enhance grid resilience and stability.
- Grid flexibility and management: Advanced grid management systems, including smart grids and demand response mechanisms, can help balance the intermittent nature of solar energy generation and ensure stable grid operation [162]. Research by Zhou et al. [163] demonstrated that advanced control strategies for solar thermal systems, integrated with energy storage, contribute to grid flexibility. By optimizing energy dispatch based on real-time grid conditions, solar thermal systems with storage can respond to grid demands efficiently. The work of Kanchev et al. [164] highlighted the use of smart grid communication and control systems in managing distributed PV generation. Real-time monitoring and control enable grid operators to balance supply and demand, mitigating the impact of intermittent solar outputs.

Future prospects: The development of advanced energy storage technologies and grid management systems will enhance the integration of solar energy into the grid, enabling greater penetration of PV technologies and solar thermal systems while maintaining grid stability.

3. Environmental impacts and sustainability:

Challenge: The production and disposal of PV modules, solar thermal systems, and energy storage components can have environmental impacts, including resource depletion and waste generation [165]. Ensuring the sustainability of these technologies throughout their life cycle is crucial.

Strategies to overcome the challenge:

- Sustainable material sourcing: Implementing responsible sourcing practices and using environmentally friendly materials can minimize the environmental footprint of PV technologies, solar thermal systems, and energy storage solutions [166].
- End-of-life management: Proper recycling and disposal of PV modules, solar thermal components, and energy storage devices can reduce waste generation and recover valuable materials for reuse [167].

Future prospects: Continued research and development in sustainable manufacturing processes, recycling technologies, and material recovery will contribute to minimizing the environmental impacts of these technologies. Circular economy approaches and resource-efficient practices will enhance the sustainability of PV technologies, solar thermal systems, and energy storage solutions.

4. Grid infrastructure and technical challenges:

Challenge: The integration of PV technologies, solar thermal systems, and energy storage solutions requires grid infrastructure upgrades and technical expertise for installation, operation, and maintenance. Insufficient grid infrastructure and a lack of technical know-how can impede their widespread adoption [168].

Strategies to overcome the challenge:

- Grid expansion and modernization: Governments and energy stakeholders need to invest in grid infrastructure upgrades, including the installation of smart grid technologies and grid-scale storage systems, to accommodate the increased integration of solar energy technologies [169].
- Workforce training and education: Developing skilled professionals and providing training programs for the installation, operation, and maintenance of solar energy systems is essential to overcome technical challenges [170].

Future prospects: With increased investments in grid infrastructure and workforce training, the technical challenges associated with the widespread adoption of PV technologies, solar thermal systems, and energy storage solutions can be addressed. As these technologies become more prevalent, technical expertise and infrastructure will improve, facilitating their integration into the energy system.

By addressing these challenges and implementing the proposed strategies, the widespread adoption of PV technologies, solar thermal systems, and energy storage solutions can be accelerated. Continued research and development, supportive policies, and collaborative efforts among governments, industry stakeholders, and research institutions are vital to overcome these challenges and pave the way for a sustainable and renewable energy future.

8. Conclusions

In this review, we have explored advancements and challenges in the adoption of PV technologies, solar thermal systems, and energy storage solutions for solar energy utilization. The environmental benefits of these technologies, including the reduction of greenhouse gas emissions and the mitigation of air and water pollution, have been well-documented. Life-cycle analysis studies have provided valuable insights into their energy payback time, carbon footprint, resource consumption, and waste generation.

Despite the numerous benefits, several challenges hinder the widespread adoption of these technologies. The cost and economic viability of PV systems, solar thermal systems, and energy storage solutions have been identified as barriers. However, ongoing efforts to reduce costs, coupled with government incentives and support, show promise for improving the economic feasibility of these technologies. Intermittency and grid integration pose challenges due to the variable nature of solar energy generation, but the integration of energy storage systems and advancements in grid management offer solutions to address these challenges.

Environmental impacts and sustainability considerations, including responsible material sourcing, recycling practices, and end-of-life management, are crucial for ensuring the long-term viability of these technologies. Circular economy approaches and sustainable manufacturing processes will contribute to minimizing the environmental footprint of PV technologies, solar thermal systems, and energy storage solutions.

The integration of these technologies requires grid infrastructure upgrades and technical expertise. Investments in grid expansion, modernization, and workforce training are essential to overcome technical challenges and facilitate the integration of solar energy systems into the energy landscape.

In conclusion, ongoing advancements in PV technologies, solar thermal systems, and energy storage solutions have demonstrated their potential to transform the energy sector and contribute to a sustainable future. Despite challenges, a continuous reduction in costs, improvements in grid integration, and commitment to environmental sustainability provide a positive outlook for their widespread adoption. Collaborative efforts among governments, industry stakeholders, and research institutions will be crucial in overcoming these challenges and accelerating the transition to a clean and renewable energy system. By harnessing the full potential of solar energy technologies, we can pave the way for a greener and more sustainable future.

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