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Review article

Review of photovoltaic and concentrated solar technologies including their performance, reliability, efficiency and storage

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ABSTRACT

The transition to sustainable energy systems is increasingly driven by the development of solar technologies like Photovoltaic (PV) and Concentrated Solar Power (CSP) systems. This study provides a comprehensive comparison of these technologies, as well as analysing their performance, reliability, scalability, and efficiency across diverse applications and climates. PV systems, with efficiencies up to 30 %, excel in adaptability and scalability, making them suitable for residential, commercial, and large-scale deployments. CSP systems, capable of achieving efficiencies of up to 35 %, offer a unique advantage in providing dispatchable power through thermal energy storage, making them ideal for large-scale grid applications in high-irradiance regions. This research emphasises the complementary strengths of PV and CSP technologies in advancing global renewable energy goals. By integrating insights into technical performance, environmental impact, and economic feasibility, the findings highlight innovative strategies to enhance energy system reliability, efficiency, and sustainability, contributing to the ongoing energy transition.

1. Introduction

One of the most urgent challenges of the 21st century is maintaining the growing energy demand while managing global environmental concerns. Rapid population growth and accelerating industrialisation have driven overall energy demand to unprecedented levels. The global population has expanded by nearly 2 billion in just one generation, with much of this increase occurring in developing countries. As they work to strengthen their economies, these regions are placing additional pressure on already strained energy resources. The need for sustainable energy alternatives has become critical as traditional sources are depleting whilst also impacting the environment, ecosystems are at risk, and global inequalities persist [1]. Addressing this growing demand for energy without causing environmental damage requires developing and adopting renewable technologies.

The sun provides an immense and versatile source of inexhaustible free energy, capable of fulfilling humanity's energy needs many times over [2]. To put it in perspective, the sun delivers the total energy consumed by humans in a year—approximately 4.6×10^{20} joules—in just one hour [3]. With advanced technologies now being used to capture and convert solar energy into electricity, solar power offers a renewable alternative to traditional non-hydro sources. These technologies have already been successfully implemented around the globe. In theory, solar energy could meet the world's energy demands if efficient methods for its harvesting and distribution were more widely available.

Every year, the Earth receives close to four million exajoules (EJ) of solar energy, with an estimated 50,000 EJ being easily harvestable [4]. As of 2023, the global installed capacity for solar energy exceeded 1200 gigawatts (GW), a significant milestone that underscores the rapid adoption of solar technologies worldwide. This capacity is capable of powering over 300 million homes, highlighting the substantial impact of solar energy on global energy systems. However, despite its vast potential, solar energy still contributes only marginally to the global energy supply, as illustrated in Fig. 1 [5].

A significant aspect of the solar energy initiative is its ability to drastically reduce the emission of harmful greenhouse gases, such as carbon dioxide (CO_2) and methane (CH_4), which are primarily released through the burning of fossil fuels [7]. Solar energy generates electricity without producing these pollutants, directly addressing the root causes of global warming, climate change, and air pollution. By transitioning to solar power, reliance on fossil fuels decreases, significantly lowering the volume of greenhouse gases in the atmosphere. This shift can help mitigate the harmful effects of global warming and environmental

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degradation, contributing to improved air quality and public health. Solar energy thus offers a cleaner, sustainable energy alternative essential for achieving global emission reduction targets and ensuring a healthier planet for future generations.

2. Major types of solar technologies

Among the renewable energy sources suitable for power generation, mainly biomass, geothermal, and solar can provide sufficient heat energy. Out of these, solar energy offers the most significant global potential as geothermal resources are geographically limited, and biomass is not uniformly distributed [8,9]. Solar energy technologies have emerged as pivotal solutions for sustainable and renewable power sources. Among these technologies, Photovoltaic (PV) systems and solar thermal systems stand out for their ability to harness the sun's energy in distinct yet complementary ways [10]. Using solid-state semiconductor devices, PV technology converts sunlight directly into electricity, making it a versatile and scalable option for various applications.

On the other hand, solar thermal technologies, especially Concentrated Solar Power (CSP) systems, focus sunlight using mirrors or lenses to generate high-temperature heat, which is then used to produce electricity through conventional turbines. Both technologies offer unique advantages and are being increasingly deployed worldwide to address the growing demand for clean energy. However, in recent years, PV technology has become the more desirable option [11]. This can be observed from Fig. 2, wherein PV had a global installed capacity until the year 2010 of approximately 35 GW, compared with CSP's 1.5 GW only.

2.1. Photovoltaic (PV) systems

PV technology has been at the forefront of the solar revolution, with its ability to convert sunlight directly into electricity using solid-state semiconductor devices. Over the recent decades, PV technology has experienced exponential growth. PV production has doubled every two years and increased by an average of 48 % annually since 2002, making it the world's fastest-growing energy technology and energy source [13], as evident from Fig. 2. The scalability, decreasing costs, and ease of integrating PV systems into existing energy infrastructures have made them a preferred choice for residential and large-scale energy projects. By 2023, PV installations accounted for a significant portion of the global energy mix, with advancements in materials and efficiency further driving down costs and expanding its accessibility. PV technology can also produce greater outputs from lesser inputs, allowing them to be employed in numerous applications across the globe, albeit its system still needs to be improved for better results. This device's basic idea is to activate electrons by providing more energy. PV technology operates on the theory that solar radiation stimulates electrons from a lower energy state to a higher energy state. These semiconductors will then become more hole-filled and electron-free because of this activation, producing electricity [14]. Overall, PV cells can be classified into four generations - first, second, third, and fourth [15], as described below.

2.1.1. First-generation photovoltaic cells

First-generation photovoltaic (PV) cells, primarily based on crystalline silicon, were the first commercially available type of solar cells. They account for over 80 % of the world's solar energy capacity and dominate the market with a 90 % share due to their proven performance and efficiency. These cells can be classified into monocrystalline and polycrystalline silicon [16,17].

Monocrystalline Silicon Cells are crafted from high-purity silicon formed into a single continuous crystal structure. This method allows for greater electron flow, leading to efficiencies as high as 25 %. The manufacturing process, however, is complex and more expensive, making these cells costlier to produce and sell. Polycrystalline Silicon Cells are made by melting silicon and then cooling it to form multiple small crystals, known as multi-crystalline silicon. Although these cells typically achieve a lower efficiency of around 20.4 %, they are more affordable due to simpler production methods that generate less material waste. Advancements such as ribbon silicon technology are helping to further lower production costs [18,19].

These first-generation cells perform best at lower temperatures and require less space for the same energy output. However, their efficiency declines at higher temperatures, a major drawback for their use in hotter climates. To improve performance, designs like Emitter Wrap-Through (EWT) cells, which have laser-drilled holes to increase surface area and enhance light absorption, have been developed. This innovation improves efficiency while reducing overall production costs [20].

Overall, first-generation PV cells remain the most widely used due to their efficiency, durability, and extensive experience in their production and application [21].

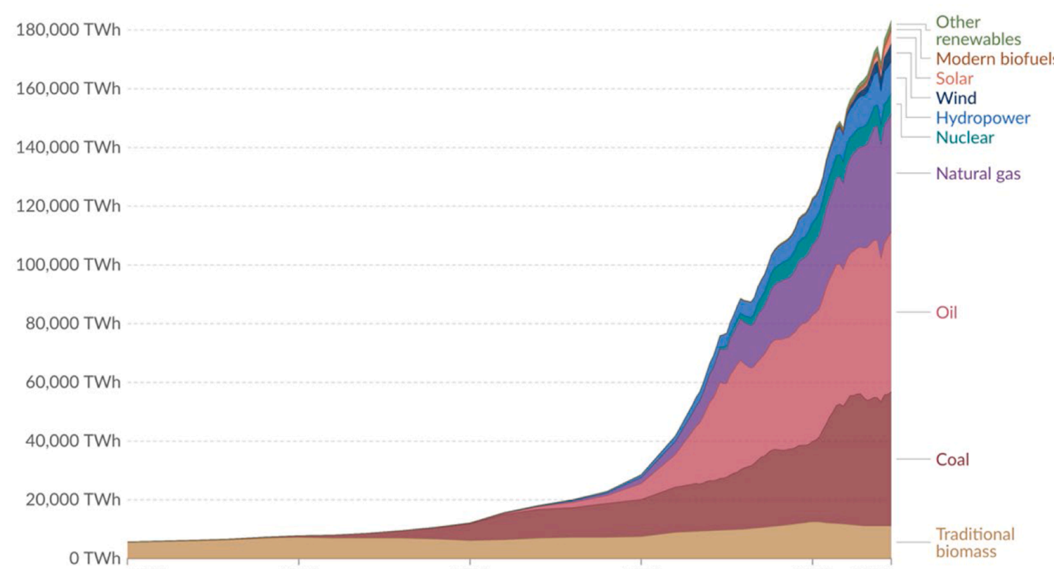

Fig. 1. Global energy supply by various sources [6].

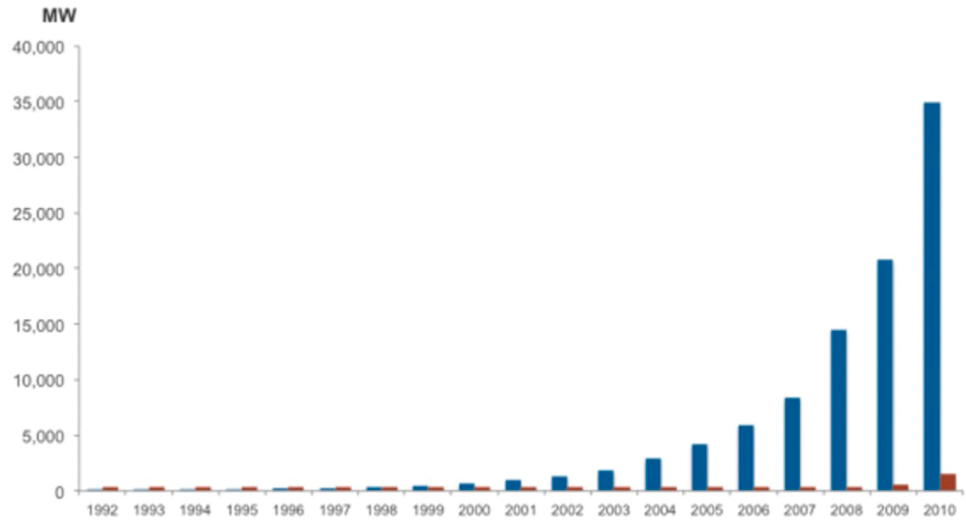

Fig. 2. Evolution of PV and CSP global installed capacity (MW) [12].

2.1.2. Second-generation photovoltaic cells

Second-generation PV cells, also known as thin-film solar cells, were developed to reduce material costs and offer more versatile applications compared to first-generation crystalline silicon cells. Thin-film technology uses significantly less semiconductor material, resulting in lower production costs. However, these cells typically have lower efficiencies, which limits their market share despite the cost benefits.

There are various types of thin-film cells, with the most common being amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) cells [22]. Amorphous silicon (a-Si) cells are one of the earliest thin-film technologies. They use less material than crystalline silicon cells and can be produced using roll-to-roll manufacturing, which is cost-efficient. However, their efficiency is lower, typically between 5 % and 12 %, and they suffer from degradation over time, dropping by up to 20 % after prolonged use due to the Staebler–Wronski effect [18,23].

Cadmium telluride (CdTe) cells are more efficient than a-Si cells, with an efficiency of around 17 %. They are relatively easy and inexpensive to manufacture due to the high light absorption properties of CdTe. However, their use is limited by the toxicity of cadmium and the scarcity of tellurium, which poses both environmental and supply chain concerns [18,24].

Copper indium gallium selenide (CIGS) cells offer even higher efficiencies, reaching up to 20 % in laboratory conditions. Commercially, their efficiency ranges from 12 % to 14 %. Despite their promise, the manufacturing process for CIGS cells is complex and expensive, and the scarcity of some elements, such as indium, further limits large-scale adoption [18,24].

Second-generation cells are generally more flexible and can be used in a wider range of applications, including on curved surfaces and flexible substrates. However, their lower efficiency compared to traditional crystalline silicon cells and the challenges associated with material toxicity and scarcity are key drawbacks. Nonetheless, ongoing research aims to improve the performance and sustainability of thin-film PV technologies.

2.1.3. Third-generation photovoltaic cells

Third-generation photovoltaic (PV) cells represent a significant advancement over earlier generations, focusing on achieving high efficiency and cost-effectiveness. These cells employ novel materials and structures, such as quantum dots, quantum wells, and organic compounds, to enhance their performance [25,26]. Technologies in this generation range from high-efficiency systems like III-V multi-junction cells, often used in space applications, to lower-cost alternatives like dye-sensitized and organic solar cells. Some, like perovskite solar cells, have demonstrated high efficiencies while maintaining relatively low production costs, making them promising for widespread adoption.

Many third-generation PV cells aim to break through the Shockley-Queisser limit, which caps conventional silicon-based cells at 31–41 % efficiency. Multi-junction and quantum-structured cells, for instance, concentrate sunlight to increase energy absorption, potentially achieving higher power conversion efficiencies [27]. However, these high-efficiency systems are still largely in the research and development phase, with challenges including material stability and manufacturing complexity [28]. Third-generation technologies are particularly innovative, with options like quantum dot-based cells, perovskites, and dye-sensitized cells offering flexibility in design and application, but each comes with trade-offs in terms of efficiency, durability, and toxicity.

2.1.4. Fourth-generation photovoltaic cells

Fourth-generation photovoltaic (PV) cells, often referred to as hybrid inorganic cells, combine the low cost and flexibility of polymer thin films with the stability of various nanostructures, including metal nanoparticles, metal oxides, carbon nanotubes, and graphene. These innovative devices, sometimes called "nanophotovoltaics," are positioned as the future of solar technology, promising significant improvements in efficiency, cost-effectiveness, and environmental sustainability [29].

Graphene plays a crucial role in fourth-generation solar cells due to its unique properties, including high carrier mobility, low resistivity, and excellent optical transmittance. These characteristics make graphene an ideal candidate for enhancing the performance of PV devices. In these applications, graphene can serve various functions, such as a transparent electrode, charge transport material, and protective layer against environmental degradation. Graphene-based solar cells include organic bulk heterojunction (BHJ) cells, dye-sensitized solar cells (DSSCs), and perovskite cells, with energy conversion efficiencies exceeding 20.3 % for perovskite solar cells and around 10 % for BHJ organic solar cells. The combination of graphene with silicon in Schottky junction solar cells has been explored, allowing for efficient charge extraction and transport [30].

The fabrication of graphene for PV applications is vital to achieving the desired performance. Methods for synthesising graphene can be categorised into top-down and bottom-up approaches. The top-down method involves intercalating and exfoliating graphite into graphene sheets, while the bottom-up method produces graphene from molecular precursors through chemical vapour deposition (CVD) or epitaxial growth. The synthesis method significantly influences the resulting graphene's structure, morphology, and electrical properties. While graphene can absorb about 2.3 % of incident white light despite its atomic thickness, incorporating it into silicon solar cells enhances optical and electrical performance. The optical transparency and electrical conductivity of graphene vary with the number of layers; increasing layers decreases resistance but also reduces transparency [31].

Fourth-generation PV cells promise enhanced affordability and flexibility, primarily due to their reliance on low-cost materials and innovative designs. Graphene's mechanical strength and flexibility further extend the potential applications in plastic electronics and optoelectronics. However, challenges remain, including the need for reliable methods to deposit well-ordered graphene monolayers and ensure strong adhesion to substrates. Despite its advantages, graphene exhibits poor hydrophilicity, complicating the design of solution-processed devices. This issue can potentially be mitigated through surface modifications [32]. Overall, the unique properties of graphene and other nanomaterials herald a new era of advanced PV technologies capable of addressing current limitations in efficiency and manufacturing costs.

2.2. *Concentrated solar power (CSP) systems*

Concentrated Solar Power (CSP) systems represent another critical component of the solar energy landscape. Unlike PV, which directly converts sunlight into electricity, CSP systems use mirrors or lenses to concentrate solar energy onto a small area, generating heat that can be used to produce electricity through conventional turbines. CSP technology is particularly advantageous in regions with high solar irradiance, where it can provide a stable and continuous power supply, especially when integrated with thermal storage systems. Although CSP currently contributes a smaller share of global solar capacity compared to PV, its potential for large-scale energy production and storage makes it a key player in the future of solar energy. Among the various forms of CSP technology, the most mature ones are [33,34]:

- Parabolic Trough Systems
- Solar Power Towers
- Linear Fresnel Reflectors
- Dish Stirling Systems

2.2.1. *Parabolic trough systems*

Parabolic trough concentrated solar power (PTC CSP) technology is the most established form of concentrated solar power, with about 90 % of commercial CSP plants utilising this design. In 2018, PTC technology contributed to 70 % of the growth in CSP power generation, resulting in over 1 GW of projects under construction [35]. Currently, eighty-seven operational PTC plants are generating a total capacity of 4947 MW.

A PTC CSP plant consists of numerous parabolic troughs that focus sunlight onto absorber tubes at their focal lines, achieving concentration ratios of 15 to 45 suns [36] and temperatures up to 550 °C [37]. To minimise thermal losses, these receiver tubes, typically made of stainless steel, are enclosed in a glass tube, often with a vacuum layer for insulation. A schematic of the PTC with a tube receiver is shown in Fig. 3.

Efficient operation relies on a single-axis tracking system that aligns the troughs to follow the sun's path [38], usually with a north-south orientation to optimise solar capture [39,40,41]. The heat transfer fluid (HTF), commonly thermal oils or molten salts, circulates through the absorber tubes, collecting thermal energy and transporting it to the steam generation system [39].

PTC systems convert solar irradiation into heat for electricity generation through the Rankine cycle [42,43]. Each trough is designed with highly polished reflective surfaces, achieving reflectivity rates of 95 % [44]. The overall efficiency of a parabolic trough collector depends on both its optical and thermal performance, with ongoing research aimed at improving these aspects to enhance energy yield and system performance.

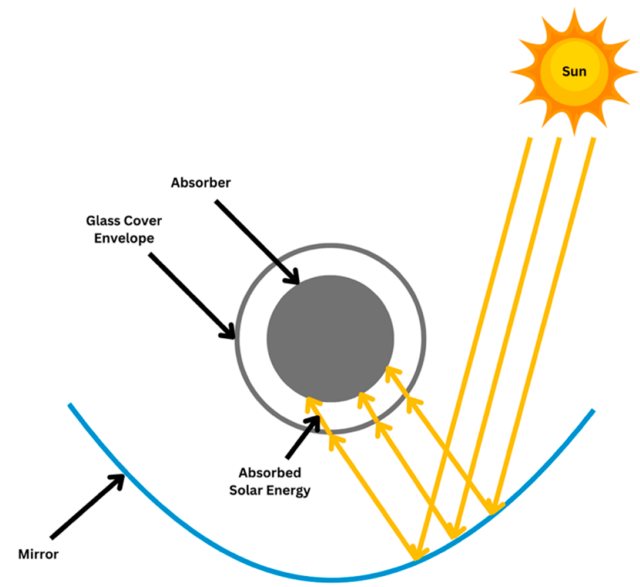

Fig. 3. Schematic of PTC cross-section with tube receiver (absorber).

2.2.2. *Solar power towers*

A solar power tower (SPT) operates by using a field of heliostats, which are dual-axis tracking mirrors, to concentrate sunlight onto a central receiver mounted atop a tower, as shown in Fig. 4. These heliostats are strategically arranged to direct the solar radiation towards the receiver, where a heat-transfer fluid (HTF), such as molten salt or water-steam, is heated to temperatures ranging from 500 °C to 1000 °C [45]. This concentrated heat can then be used to drive a thermodynamic cycle for electricity generation or stored for later use during periods of insufficient sunlight, such as cloudy weather or nighttime [46].

The SPT system is highly efficient due to its ability to achieve higher operational temperatures than other CSP technologies. The receiver absorbs the concentrated solar energy, and the heat is transferred to the HTF, which then circulates through a heat exchanger to produce steam for power generation if molten salt is used. In cases where water-steam is the HTF, a separate heat exchanger is not necessary, streamlining the process. However, despite the system's efficiency, solar towers face energy losses primarily due to the shading, blockage, and spillage of sunlight as it reflects from heliostats, as well as thermal losses in the receiver, piping, and storage tanks. The heliostat field is responsible for a significant portion of the total investment in an SPT plant and contributes to around 40 % of the solar energy losses. Still, the system's ability to store excess thermal energy through thermal energy storage (TES) offers a major advantage, allowing for continued power production even when solar radiation is insufficient [47]. Advances in this technology, such as using supercritical carbon dioxide as the working fluid instead of steam, are being explored to further enhance its efficiency and performance.

2.2.3. *Linear fresnel reflectors*

Linear Fresnel Reflectors (LFRs) are a type of solar concentrating technology that uses rows of flat or slightly curved mirrors to direct sunlight onto a fixed linear receiver positioned several meters above the mirrors. A schematic of the LFR is presented in Fig. 5. Inside the receiver are tubes where a working fluid circulates, absorbing heat from the concentrated sunlight. This heat can then generate steam for power production or be used in industrial processes. The mirrors in LFR systems are simpler and cheaper to produce compared to those in parabolic trough systems, making the overall system more cost-effective [48].

Although LFR systems tend to be less efficient than other types of CSP

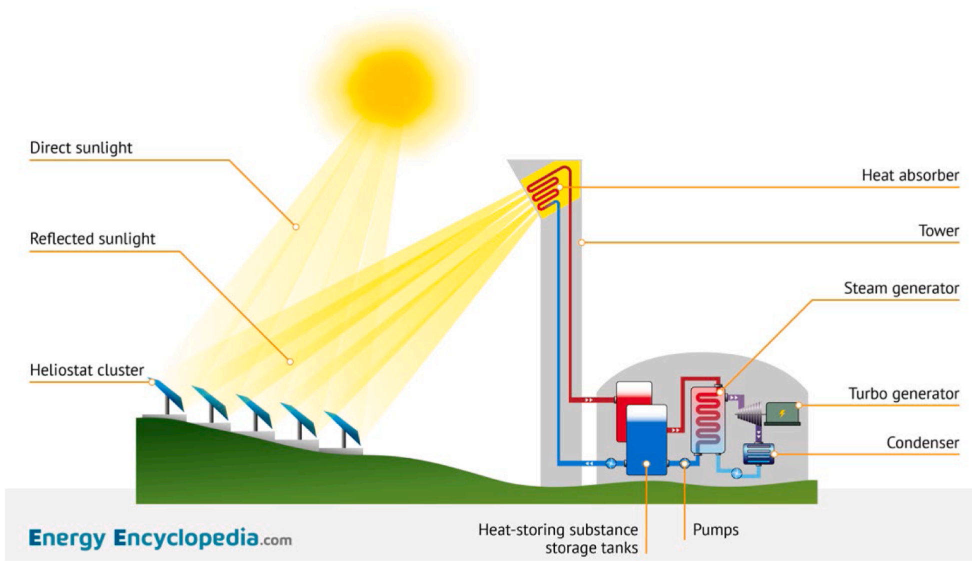

Fig. 4. Schematic of a Solar power tower plant. Credit: EnergyEncyclopedia.com.

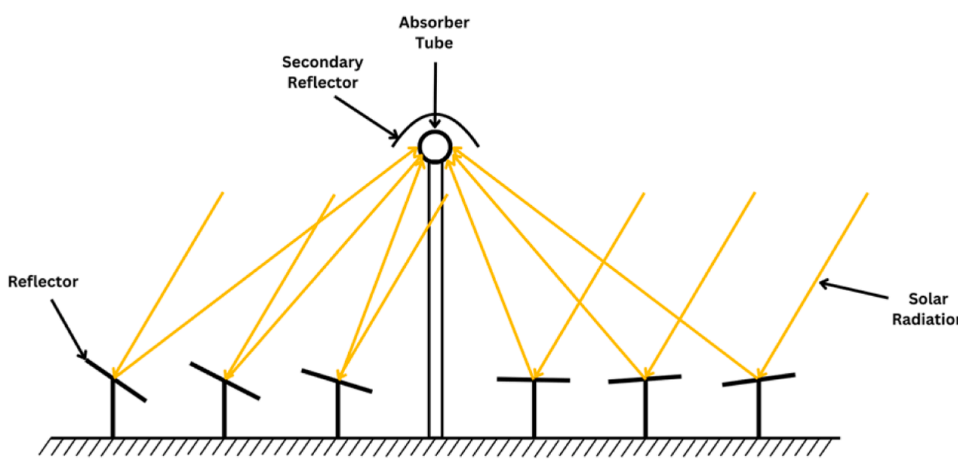

Fig. 5. Schematic of a Linear Fresnel Reflector.

technologies, such as parabolic troughs or solar towers, they offer advantages such as lower land requirements and reduced vulnerability to wind due to their low-profile design. LFRs can also be scaled to different sizes, from small local installations to large grid-connected systems producing significant amounts of electricity.

To boost efficiency, LFR systems often feature other concentrators like compound parabolic concentrators (CPCs), which increase the amount of sunlight reflected onto the absorber tubes [49]. While this design improves optical performance, it also raises system costs. Another approach to enhancing efficiency is the use of trapezoidal receivers or molten salt as a heat transfer medium, enabling operation at higher temperatures than conventional thermal oils [50].

Compact versions of LFR, known as CLFR, group several reflectors closely together to maximise energy capture [51]. LFRs are also being explored in hybrid systems, such as those used for water desalination, where the heat from the reflectors is applied to desalination processes. While LFRs typically have lower optical and thermal efficiencies compared to other CSP systems, their lower cost and adaptability make them an attractive option for a variety of solar power applications.

2.2.4. *Dish stirling systems*

The dish Stirling system is a type of Concentrated Solar Power (CSP) technology that utilises a parabolic dish to focus sunlight onto a receiver located at its focal point, as shown in Fig. 6. This system tracks the Sun along two axes to maintain optimal alignment throughout the day. As sunlight is concentrated, the working fluid, typically a gas such as hydrogen or helium, is heated to high temperatures, often ranging from 250 °C to 700 °C. This thermal energy is then transferred to a Stirling engine, which converts it into mechanical power by expanding and contracting the working fluid within a closed system [52].

The Stirling engine operates by cycling the gas between hot and cold states, producing a rising and falling pressure that drives pistons, converting the motion into mechanical power [53]. Unlike traditional engines, the Stirling engine benefits from using an external heat source, allowing it to achieve higher efficiency and scalability. This external heat source flexibility allows for integration into solar thermal systems, reducing the complexity and cost of power generation [54]. Due to its high efficiency and relatively straightforward design, the dish Stirling system is often highlighted as a promising option for decentralised power generation in both industrialised and developing regions [55,56].

A key advantage of the parabolic dish is its modularity, which makes it suitable for small-scale installations or larger power plants, depending on energy demands. These systems are noted for their high solar-to-electric conversion efficiency, with records of over 30 % efficiency achieved in controlled environments [57]. Innovations in the design, such as advanced tracking mechanisms and improved receiver

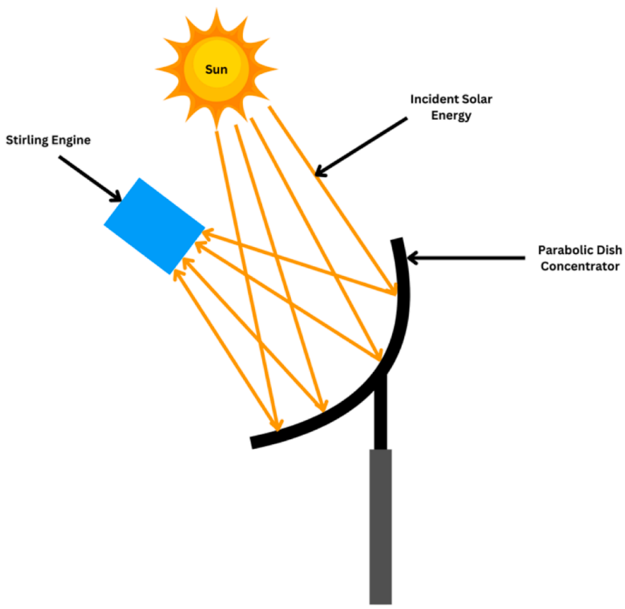

Fig. 6. Schematic of the dish stirling system.

technology, continue to push the performance boundaries of dish Stirling systems.

Applications of this technology include stand-alone power generation, remote area energy supply, and potential integration into hybrid systems that combine solar power with other renewable sources. Advances in materials science, particularly in developing more durable and efficient reflective surfaces, are expected to further improve these systems' overall performance and cost-effectiveness [58]. Additionally, ongoing research focuses on enhancing the thermodynamic efficiency of Stirling engines by optimising working fluid properties and improving thermal energy storage solutions, ensuring the viability of dish Stirling systems as a sustainable energy source in the future.

Recent advancements in technology are various hybrid systems, which integrate CSP with conventional energy sources or other renewables. These have also shown promise in enhancing overall efficiency and reliability. For instance, coupling CSP with natural gas or biomass can facilitate continuous energy supply and improve grid stability. As research and development in CSP technology continue to progress, innovations in materials, thermal storage solutions, and system design are anticipated to further optimise efficiencies across all CSP types, ultimately contributing to the global shift towards sustainable energy generation.

3. Performance, reliability, and efficiency of solar technologies

3.1. Comparing performance of different pv cells

The evolution of photovoltaic (PV) technology has led to the development of distinct generations of solar cells, each offering unique efficiencies and applications. First-generation solar cells, primarily made of crystalline silicon, offer efficiencies ranging from 15 % to 22 %, and they are known for their reliability but higher costs. These cells are well-established and widely used, but they are limited by the Shockley-Queisser efficiency threshold. Second-generation thin-film cells, like cadmium telluride and amorphous silicon, achieve efficiencies between 10 % and 12 %, providing flexibility and lower production costs despite environmental concerns. Third-generation cells, including perovskite, dye-sensitized, and organic solar cells, show efficiencies from 10 % to over 25 %, leveraging innovative materials and designs to enhance performance while addressing stability and scalability challenges. Fourth-generation hybrid inorganic cells utilising advanced materials like graphene have demonstrated efficiencies exceeding 20 %, emphasising cost-effectiveness and environmental sustainability. This progression highlights the solar industry's commitment to improving energy conversion efficiency and expanding the application of photovoltaic technology across diverse environments. A summary of each solar cell type and the average efficiencies for each generation are presented in Fig. 7.

3.2. Comparing performance of different CSP systems

The efficiency of Concentrated Solar Power (CSP) systems varies significantly among different technologies, influenced by factors such as design, operational conditions, and thermal management methods. Among the primary CSP technologies, parabolic trough systems typically exhibit a solar-to-electric efficiency ranging from 15 % to 20 %. This moderate efficiency is attributed to the system's ability to track the sun and concentrate sunlight onto a receiver, although it is often limited by thermal losses and the heat transfer medium's properties. Linear Fresnel reflectors (LFR) generally yield slightly lower efficiencies, around 10 % to 18 %, due to higher optical losses associated with their flat reflectors and the geometric limitations in concentrating solar energy.

In contrast, dish Stirling systems stand out with efficiencies exceeding 30 %, primarily due to their ability to operate at higher temperatures and direct thermal-to-mechanical energy conversion via the Stirling engine. This advantage allows dish systems to maximise energy capture from solar radiation, although their practical deployment may be constrained by higher costs and complexity compared to other CSP technologies. Furthermore, solar power towers can achieve efficiencies in the range of 20 % to 25 % by utilising central receivers and advanced thermal storage systems, which enable them to store heat for later electricity generation, thus providing dispatchable power even when sunlight is not available. A comparison of the efficiency along with other parameters of the CSP technologies is presented in Table 1.

3.3. Comparison of PV vs CSP technologies

Building on the analysis of the performance, reliability, and efficiency of solar technologies, it becomes crucial to examine the comparative merits of Photovoltaic (PV) and Concentrated Solar Power (CSP) systems within these parameters. These two approaches, while distinct in their mechanisms and applications, both offer critical contributions to solar energy adoption. CSP systems are often regarded as more efficient under ideal conditions, with solar-to-electric conversion efficiencies of 25–35 % for technologies like solar towers and dish Stirling engines and even higher in advanced configurations. This superior performance is driven by their ability to operate at high temperatures using thermodynamic cycles, such as the Rankine or Brayton cycles. PV systems, on the other hand, have demonstrated consistent improvements, with modern crystalline silicon panels achieving efficiencies of 20–25 % and tandem perovskite-silicon cells pushing these boundaries further. Despite slightly lower peak efficiencies, PV systems hold an advantage in their ability to capture both direct and diffuse sunlight, enabling greater versatility in diverse weather conditions. Notably, innovative designs such as the sunflower-inspired solar tree demonstrate enhanced performance, with studies showing 16–23 % higher energy output compared to traditional flat PV modules. These designs also maintain module temperatures up to 10 °C lower, a factor that significantly improves conversion efficiency in high-temperature environments [61].

The adaptability of PV systems stands out when considering their practical performance across varying geographic and environmental contexts. Unlike CSP, which relies heavily on direct normal irradiance (DNI) and performs best in regions with clear skies and high solar irradiance, PV systems can maintain significant output even in partially cloudy or hazy environments. Moreover, PV systems typically exhibit

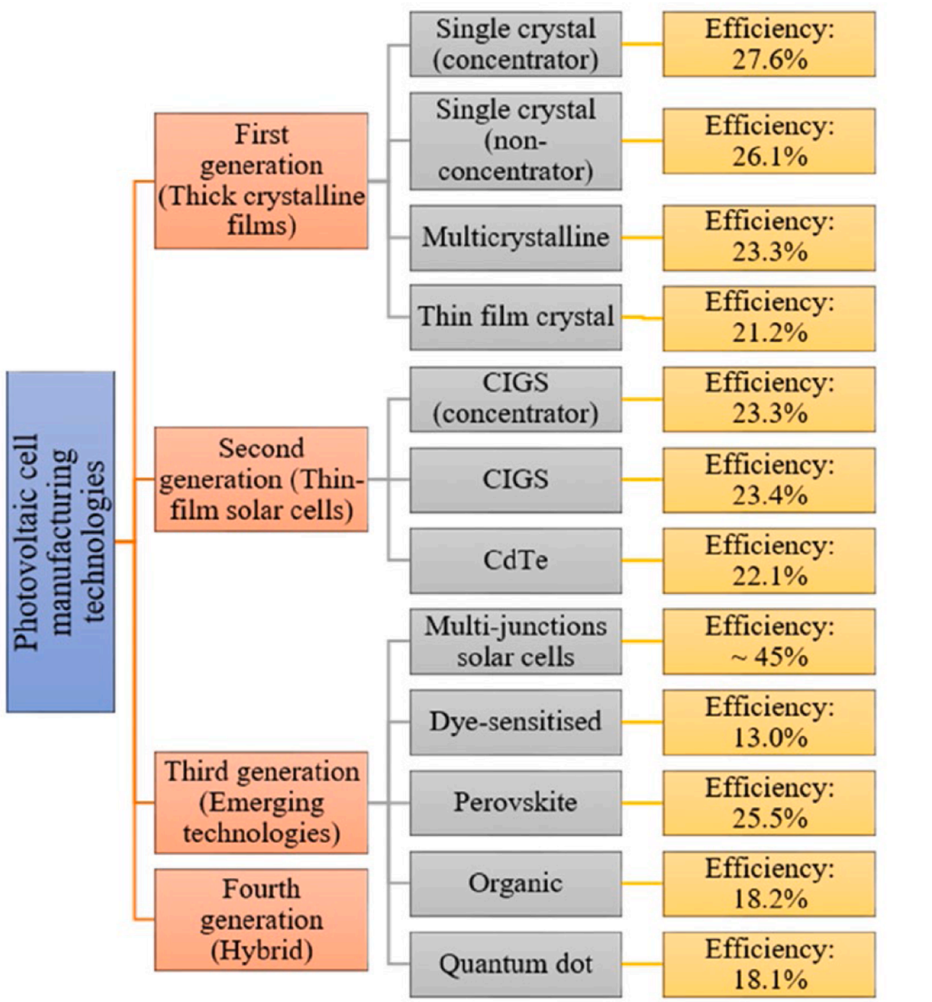

Fig. 7. Examples of PV cell efficiencies [59].

Table 1
Comparison of various parameters of CSP technologies [60].

	PTC	SPT	LFR	PDS
Power Output Range (MW)	10–250	10–100	5–250	0.01–1
Operational Temperature Limits (°C)	150–400	300–1200	150–400	300–1500
Solar Concentration Ratio	50–90	600–1000	35–170	< 3000
Conversion Efficiency (%)	15–20	20–25	10–18	20–32
Estimated Cost Category	Cost-effective	High capital investment required	Low to moderate cost	Considered very expensive
Power Cycle	Utilizes Steam Rankine and Organic Rankine cycles	Operates with Steam Rankine and Brayton cycle (gas turbine)	Compatible with Steam Rankine and Organic Rankine cycles	Works with Stirling engine, Steam Rankine, and Brayton cycle
Technology Readiness Level	Well-established and commercially deployed	Developing but gaining adoption	Intermediate maturity with industrial applications	Limited commercial deployment
Future Development Potential	Minimal scope for efficiency improvements	Strong potential for efficiency gains and cost reduction	Moderate room for enhancement	Significant growth potential with mass production
Key Advantages	Proven long-term reliability; flexible modular system; suitable for hybrid operation with fossil fuels	High energy conversion efficiency; adaptable to hybrid systems with fossil fuel backup; modular scalability	Simple, cost-effective design; easy to construct; suitable for industrial heat applications	Exceptional efficiency levels; modular scalability; well-suited for off-grid power generation
Challenges & Limitations	Moderate efficiency compared to alternatives; requires water for cleaning and cooling; complex structural components	High initial cost; maintenance-intensive; requires significant water for cleaning and cooling	Lower efficiency than some other CSP options; operational temperature restrictions	Not widely adopted; no integrated thermal storage; currently limited commercial viability

greater land use efficiency, producing more electricity per unit area than CSP installations. CSP plants, due to their reliance on extensive heliostat fields or parabolic troughs, often require significant land area, making their deployment more suited to sparsely populated or desert regions.

Reliability further distinguishes these technologies. CSP systems excel in providing dispatchable power thanks to their integration with thermal energy storage (TES), such as molten salt systems, which decouple electricity generation from sunlight availability. This allows CSP plants to generate power consistently during cloudy periods or even after sunset. In contrast, PV systems are more dependent on real-time sunlight, and while battery storage is increasingly used to offset this limitation, it remains costlier and less developed than CSP's TES solutions. Over time, degradation rates also play a role in reliability, with CSP systems typically experiencing less annual efficiency loss (approximately 0.2 %) compared to PV systems (around 0.5 %).

In operational terms, CSP systems often involve higher maintenance demands due to their moving components and high-temperature operations, which require regular upkeep, including heliostat cleaning and the management of thermal storage materials. PV systems, with their simpler architecture and absence of moving parts, tend to be less maintenance-intensive and easier to manage over their operational lifespan. However, CSP's ability to achieve higher capacity factors—-thanks to its thermal storage capabilities—further underscores its efficiency in delivering consistent power. PV systems, while capable of high energy output during peak sunlight hours, are limited by their inability to generate electricity once the sun sets, resulting in lower capacity factors.

Ultimately, the choice between PV and CSP is influenced by the specific requirements and conditions of the installation site. CSP systems thrive in high-irradiance regions with ample land availability, where their thermal storage capabilities and higher conversion efficiencies offer distinct advantages for large-scale, grid-connected applications. PV systems, in contrast, provide unmatched flexibility and scalability, making them suitable for a broader range of climates and installations, from residential rooftops to expansive solar farms. Together in hybrid systems (discussed in next section), these technologies embody complementary strengths, driving the global shift toward sustainable energy through their respective capabilities in scalability, reliability, and efficiency [62].

Table 2 provides a detailed comparison of PV and CSP technologies, summarising their performance characteristics, environmental impacts, and ideal applications to illustrate their respective roles in the energy transition.

4. Photovoltaic/Thermal (PV/T) hybrid systems

Photovoltaic Thermal (PV/T) technology is a hybrid system that combines photovoltaic (PV) modules and solar thermal collectors to generate both electricity and heat from the same surface area [63]. This can be presented through a network of solar conversion technologies shown in Fig. 8. This system addresses the inherent inefficiency of traditional PV modules, which convert only a fraction of the solar energy into electricity—typically 10–20 %—while the rest is lost as heat. By capturing and utilising this waste heat, PV/T systems significantly improve the overall energy conversion efficiency, making them an appealing solution for both electricity generation and thermal energy needs.

There are two primary configurations of PV/T systems [64]: (1) air-based and (2) water-based. Air-based PV/T systems use air as the heat transfer medium, which circulates behind the PV panels to absorb the heat and can be used for space heating or ventilation purposes. These systems are relatively simple in design and are particularly effective in applications where hot air is needed, such as building heating. Water-based PV/T systems, on the other hand, use water or another liquid to absorb the heat from the PV modules. This setup is more efficient at capturing heat than air-based systems, making it ideal for applications requiring hot water, such as domestic water heating or industrial processes [65]. Integrating these two energy forms—electricity and heat—makes water-based PV/T systems particularly attractive in regions with high thermal energy demands.

PV/T systems can also be categorised based on whether the system is glazed or unglazed (sometimes also called covered and uncovered) [66, 67]. This is illustrated in Fig. 9. Glazed PV/T systems have an additional layer of transparent material over the PV cells, which reduces heat loss by trapping the heat underneath the glazing. This configuration results in higher thermal efficiency but can slightly reduce the electrical output due to the increased reflection of sunlight. Unglazed PV/T systems, on the other hand, are simpler in design and allow for higher electrical

Table 2
Summary of PV vs. CSP technologies.

Parameter	Photovoltaic (PV) Systems	Concentrated Solar Power (CSP) Systems
Efficiency	20–25 % for modern silicon panels; up to 30 % with tandem perovskite cells.	15–32 %, depending on technology (e.g., parabolic trough: ~15–20 %; dish Stirling: ~30 %).
Energy Capture	Captures both direct and diffuse sunlight, adaptable to various climates.	Relies heavily on direct normal irradiance (DNI); performs best in sunny regions.
Energy Storage	Requires batteries (e.g., lithium-ion); scalable but expensive for long durations.	Thermal energy storage (TES) using molten salts or PCMs; more cost-effective for long-duration storage.
Scalability	Highly scalable: suitable for rooftop systems to large solar farms.	Suitable for large-scale installations; requires significant land area.
Land Use Efficiency	Higher energy output per unit area.	Requires more land due to heliostat fields or parabolic mirrors.
Reliability	Affected by real-time sunlight availability; needs external storage solutions.	Provides dispatchable power via thermal storage, ensuring steady output.
Maintenance	Low-maintenance; no moving parts in standard systems.	Higher maintenance due to moving parts and high-temperature operations.
Installation Costs	Generally lower than CSP; continuous cost reductions due to mass production.	Higher upfront costs; heavily influenced by the storage system and land preparation.
Ideal Conditions	Can operate in both cloudy and clear conditions; suitable for diverse locations.	Requires clear skies with high DNI; best in deserts and arid regions.
Maturity	Highly mature with widespread adoption globally.	Medium maturity; limited to regions with strong solar resources.
Applications	Residential rooftops, commercial buildings, utility-scale farms.	Utility-scale power plants, industrial applications with high-temperature needs.
Environmental Impact	Minimal; dependent on battery production and disposal impact.	Water-intensive; needs innovations like dry cooling to mitigate resource usage.

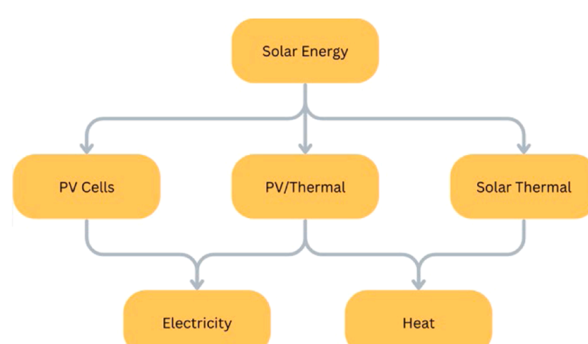

Fig. 8. Network of different solar technologies.

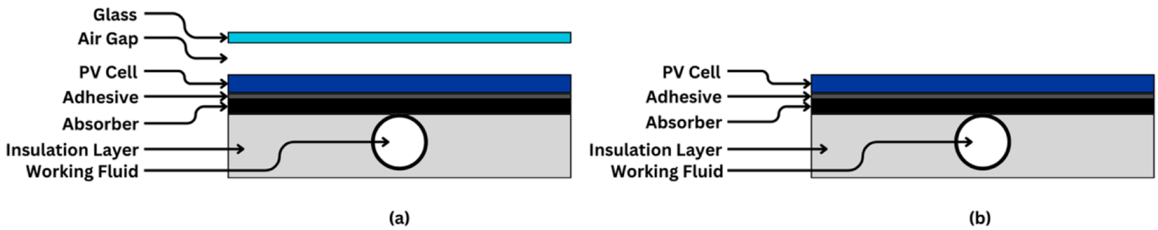

Fig. 9. Schematic of (a) covered and (b) uncovered PV/T flat module.

efficiency, though they typically have lower thermal efficiency due to greater heat loss. The choice between glazed and unglazed systems depends on the specific energy needs of the application, with glazed systems being more suitable for heating-intensive uses and unglazed systems favoured for maximising electrical output.

One of the significant advantages of PV/T technology is its ability to provide both electrical and thermal energy in a compact, integrated system. This dual functionality makes PV/T systems particularly well-suited for applications such as zero-energy buildings, where both types of energy are required to meet the energy needs of the occupants [64]. By using a single installation to generate both heat and electricity, PV/T systems can reduce the total cost and space requirements compared to installing separate PV and thermal systems. This architectural uniformity is especially beneficial in urban environments, where space is often limited, and energy efficiency is a priority.

Furthermore, PV/T systems help improve the efficiency of the PV modules themselves. As PV modules operate, they tend to heat up, and this increase in temperature reduces their electrical efficiency. In a PV/T system, the thermal collector helps to cool the PV modules by transferring the excess heat to the cooling medium (air or water). This cooling effect allows the PV modules to operate at a lower temperature, thereby improving their electrical efficiency and extending their operational lifespan. This dual energy production and improved performance make PV/T systems a compelling option for maximising the use of solar energy.

PV/T systems are an evolving technology with great potential for enhancing solar energy utilisation. While they are not yet as widespread as standalone PV or solar thermal systems, ongoing research and development are driving improvements in their efficiency and cost-effectiveness. As the demand for renewable energy grows and the need for more efficient solar technologies increases, PV/T systems are likely to play a more prominent role in the global energy landscape, particularly in applications where both heat and electricity are required.

5. Energy storage systems

Energy storage systems are critical in enhancing the reliability and efficiency of renewable energy technologies, particularly photovoltaic (PV) and concentrated solar power (CSP) systems. These storage systems allow for the management of the intermittent nature of solar energy, ensuring a consistent supply of electricity even during periods of low generation. Energy storage methods can be classified into three primary types: mechanical, electrochemical, and thermal storage [68,69,70,71]. Mechanical storage encompasses systems like pumped hydro storage (PHS) and compressed air energy storage (CAES), while electrochemical storage includes batteries and supercapacitors. Thermal storage is primarily utilised in CSP technologies. Each type of energy storage presents unique advantages and challenges tailored to the specific needs of PV and CSP systems [72].

5.1. Energy storage systems for PV technology

Photovoltaic systems convert sunlight directly into electricity, necessitating energy storage solutions to manage the inherent variability of solar generation. The most common energy storage methods for PV systems include electrochemical storage, such as lead-acid batteries, lithium-ion batteries, and supercapacitors, alongside mechanical storage options like pumped hydro storage (PHS) and compressed air energy storage (CAES). These storage systems vary significantly in terms of energy capacity, efficiency, and operational characteristics, making them suitable for different applications within the PV landscape.

Lithium-ion (Li-ion) batteries are the most prevalent form of electrochemical storage in PV applications due to their high energy density, efficiency, and longevity [73,74]. These batteries operate by transferring lithium ions between a cathode and an anode during charging and discharging. Their high efficiency, typically ranging between 85 % and 95 %, and relatively fast response times make them particularly well-suited for balancing short-term energy supply and demand in both residential and commercial PV systems. Lithium-ion batteries also support modularity, enabling scalable solutions from small home systems to large utility-scale installations. However, challenges remain, such as degradation over time, performance variability with temperature fluctuations, and higher initial costs compared to other battery technologies [75,76]. According to the International Energy Agency (IEA), the lithium-ion battery market has seen exponential growth, with prices decreasing by around 90 % since 2010, making them more accessible for PV applications [77].

Lead-acid batteries have been a traditional choice for energy storage in PV applications, especially in off-grid settings and backup power solutions. Despite having a lower energy density, approximately 30–50 Wh/kg, and lower efficiency, ranging from 70 % to 80 %, compared to lithium-ion counterparts, their affordability and robustness make them an attractive option for small to medium-sized PV systems. Lead-acid batteries consist of lead dioxide and sponge lead electrodes immersed in sulfuric acid, facilitating the electrochemical reactions necessary for energy storage. These batteries are best suited for applications where cost is a primary concern and moderate energy storage requirements are sufficient. However, their larger physical footprint, limited cycle life, and maintenance needs pose limitations for large-scale deployments [78]. The U.S. Department of Energy (DOE) notes that lead-acid batteries typically last between 3 and 5 years, which can necessitate more frequent replacements compared to newer technologies [79].

Supercapacitors, also referred to as ultracapacitors, represent another form of electrochemical storage that can complement traditional batteries in PV systems [80]. Supercapacitors provide rapid charge and discharge capabilities, enabling them to deliver high power over short periods, making them ideal for applications requiring quick bursts of energy [81]. They operate on the principle of electrostatic charge storage, offering exceptional cycle stability and efficiency, often exceeding 95 %. However, supercapacitors have a lower energy density compared to batteries, typically around 5–10 Wh/kg and a discharge rate of 5 %, which makes them less suitable for long-duration energy storage [82]. Nevertheless, when used in conjunction with batteries, they can enhance overall system performance by mitigating short-term fluctuations in energy output from PV systems. Research indicates that integrating supercapacitors with lithium-ion batteries can improve the overall efficiency and lifespan of energy storage systems.

Compressed Air Energy Storage (CAES) is a mechanical storage solution that can integrate with PV systems to address energy storage challenges. In CAES systems, excess electricity generated by PV panels is used to compress air stored in underground caverns or large tanks [83]. When energy demand spikes or solar generation dips, the compressed air is heated and released to drive turbines, producing electricity. CAES offers substantial storage capacity, making it a viable option for large-scale PV installations needing to store energy for extended periods. While CAES systems can achieve efficiencies of around 40 % to 60 %, they often require significant geological and infrastructural considerations, which can limit their applicability. The technology is expected to be 70 % efficient, with a lifespan of approximately 40 years [84].

Pumped Hydro Storage (PHS) stands out as the most widely deployed form of mechanical energy storage, constituting a significant portion of the global energy storage capacity [85]. In PHS systems, excess energy from PV systems is utilised to pump water from a lower reservoir to an upper one. During periods of high electricity demand, the stored water is released, flowing back down through turbines to generate electricity. PHS systems can achieve high efficiencies, ranging from 65 % to 80 %, and provide long-duration energy storage capabilities [86]. However, they require specific geographical conditions and substantial infrastructure, which can limit their integration with PV systems, particularly in urban environments. The International Energy Agency (IEA) indicates that PHS accounts for over 90 % of global energy storage capacity, underscoring its importance in the energy landscape [87].

A comparative chart summarising the different PV energy storage methods is presented in Table 3. Table 4 shows the technical characteristics of the various PV energy storage methods [107,108].

5.2. Energy storage systems for CSP technology

Concentrated Solar Power (CSP) systems operate primarily on the principle of converting solar energy into thermal energy, therefore making thermal energy storage (TES) systems the most compatible and efficient way for storing energy in CSP applications. The use of thermal storage allows CSP plants to continue delivering electricity even after the sun has set, providing a more stable and consistent power output compared to PV systems. Thermal energy storage systems can be classified into two main types: thermal and chemical storage. Thermal storage systems can be further divided into sensible heat storage and latent heat storage [109]. This is shown in Fig. 10. Each type offers unique advantages based on the specific thermal management needs of the CSP system.

In sensible heat storage, energy is stored by increasing the temperature of a solid or liquid medium without causing a phase change [110,111,112]. A common example of sensible heat storage in CSP systems is the use of molten salts [113]. Molten salt storage involves heating a mixture of sodium nitrate and potassium nitrate, which has a high heat capacity and can store thermal energy at temperatures up to 400 °C [114,115]. During the day, concentrated solar energy is used to heat the molten salt, which can later be utilised to generate steam in a turbine, even when sunlight is unavailable. This method provides high efficiency, often reaching 95 %, and is widely used due to its scalability and capacity for long-duration energy storage. According to the U.S. Department of Energy, CSP plants utilising molten salt technology have demonstrated operational flexibility, allowing for the provision of electricity during peak demand hours when solar generation may be insufficient [116]. However, there are challenges associated with molten salt systems, including the need for specialised materials that can withstand high temperatures without degrading and the costs associated with large-scale deployment. For instance, while the initial investment for CSP with molten salt storage can be substantial, the long-term operational costs tend to be lower than conventional fossil-fuel-based power plants.

Latent heat storage involves storing energy through phase changes, such as from solid to liquid, utilising phase change materials (PCMs) [117]. These materials are promising in thermal energy storage for CSP systems because they can store substantial amounts of energy at relatively constant temperatures during phase transitions. Commonly used PCMs include organic compounds, salts, and hydrated materials, which absorb heat when melting and release it during solidification. This phase change process allows PCMs to achieve higher energy density than sensible heat systems. In CSP applications, PCMs enhance overall efficiency in energy capture and storage. Research indicates that their integration can improve system performance, reduce costs, and increase reliability by providing stable energy output during fluctuations in solar radiation.

Moreover, PCMs can store energy at lower temperatures compared to molten salts, making them a favourable alternative in specific contexts and broadening the operational flexibility of CSP systems. However, challenges persist regarding the integration of PCMs into commercial CSP applications, particularly in terms of cost, scalability, and material compatibility. Ongoing research seeks to address these issues and optimise PCMs for broader use in CSP plants, which could significantly impact the thermal storage landscape.

Fig. 11 highlights the difference in how energy is stored for sensible and latent heat storage systems.

Chemical energy storage involves capturing and storing thermal energy through reversible chemical reactions. A prominent example of this technology is sorption-based storage, where energy is stored via adsorption or absorption processes. In these systems, materials such as zeolites or silica gels adsorb water vapour, releasing heat during the

Table 4
Comparison of technical characteristics of PV ES systems [108].

ES Technologies	Power rating (MW)	Discharge time	Capital costs ($/kW)	Round trip efficiency (%)
Batt-Li-ion	0 - 0.1	Minutes to hours	1200 - 4000	85 - 100
Batt-Lead acid	0 - 20	Seconds to hours	300 - 800	70 - 80
Supercapacitor	0 - 0.3	ms to 60min	100 - 500	90 - 100
CAES	5 - 300	1 h to 24h+	400 - 1350	70 - 80
PHS	100 - 5000	1 h to 24h+	600 - 2000	70 - 85

Table 3
Comparative chart of different ES technologies [106].

ES Technologies	Pros	Cons	Applications		References
			Power	Energy	
Li-ion	Higher power, high energy density and high efficiency	Higher manufacturing cost, special circuit required for charging	Completely capable, fully reasonable	Feasible, not practical, economical	[88,89,90,91]
Lead-acid	Lower capital cost	Short life cycle	Completely capable, fully reasonable	Feasible, not practical, not economical	[92,93,94,95]
Electrolytic Supercapacitors	Longer life cycle, higher efficiency	Lower energy density	Completely capable, fully reasonable	Reasonable for energy applications	[96,97,98]
CAES	High capacity, lower cost	Different site requirements, need gas-based fuel	Not feasible, not cost-effective	Completely capable, fully reasonable	[99,100,101,102]
Pumped Hydro storage	Higher capacity, lower cost	Special site requirements	Not feasible, not cost-effective	Completely capable, fully reasonable	[103,104,105]

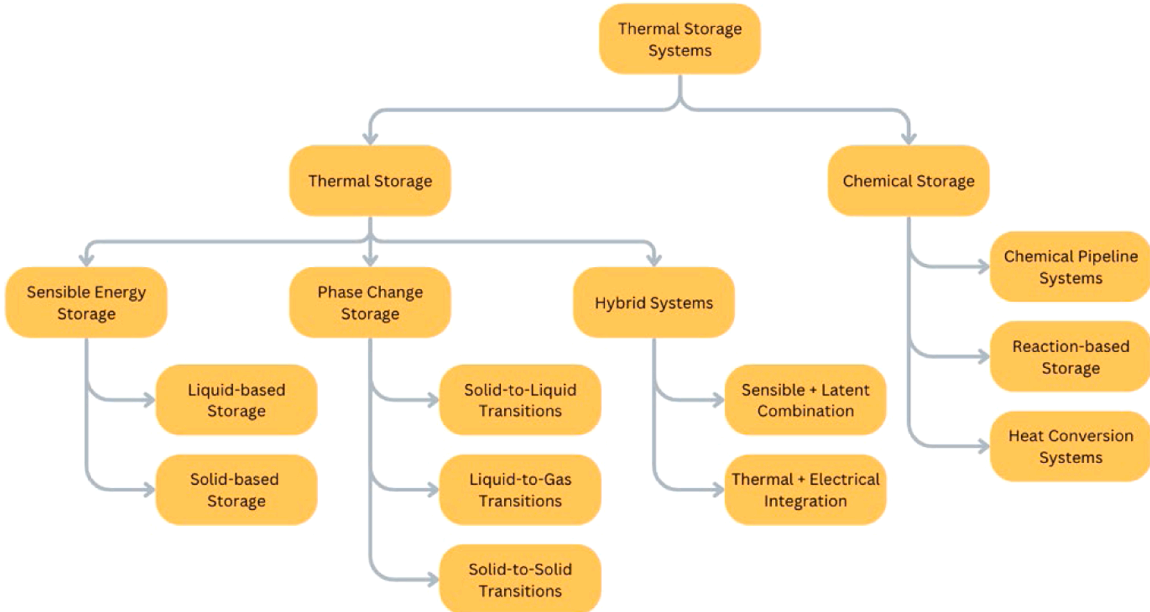

Fig. 10. Thermal Energy Storage (TES) Classification.

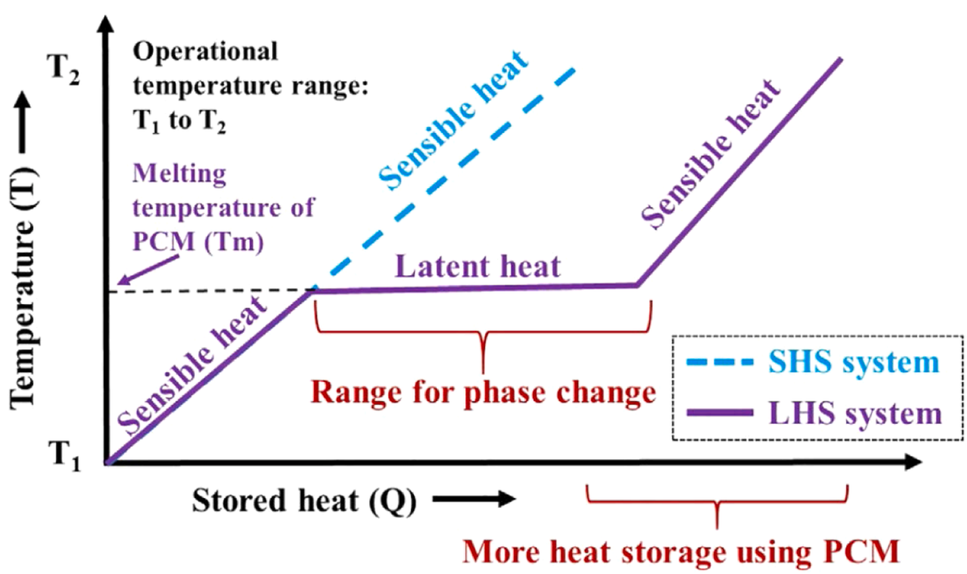

Fig. 11. Comparison of sensible and latent heat storage systems [118].

adsorption process. When energy storage is required, the material undergoes a reverse reaction, desorbing the water, which can be recharged using solar heat. Sorption storage systems offer high energy density and can maintain stored energy over extended periods with minimal heat loss, making them highly efficient, albeit more complex, than traditional thermal storage methods. Within the context of concentrated solar power (CSP) systems, sorption energy storage leverages the ability of certain materials to absorb and release heat effectively. Solid sorbents like zeolites and metal-organic frameworks (MOFs) are utilised to capture excess heat generated by the CSP plant during periods of high solar insolation. When energy demand rises or sunlight diminishes, these materials release the stored thermal energy, often used for steam production to generate electricity. One significant advantage of sorption storage is its high energy density, allowing for more compact storage solutions compared to traditional methods like molten salt.

Furthermore, sorption systems exhibit minimal thermal losses, enhancing their efficiency for long-duration storage applications. Current research indicates that integrating sorption materials can substantially improve the operational flexibility of CSP systems, providing dispatchable power even during prolonged periods of low solar radiation. However, challenges such as material degradation and the complexity of system design continue to be areas of ongoing investigation and development [119,120,121].

6. Future challenges

6.1. Challenge areas of PV technology

While photovoltaic (PV) systems offer immense promise as a renewable energy source, several challenges limit their efficiency, reliability, and overall performance. These challenges can be broadly categorised into factors related to environmental conditions, manufacturing defects, system design, and grid integration.

One of the primary factors affecting the efficiency of PV systems is their sensitivity to environmental conditions. Solar radiation is the primary energy source for PV panels, and variations in its intensity due to factors like shading and atmospheric changes significantly impact performance [122,123]. Shading, which can occur from buildings, trees, or even cloud cover, reduces the amount of sunlight hitting the PV panels, leading to a mismatch problem. This mismatch occurs when certain cells or modules receive less sunlight, causing them to underperform compared to the rest of the system, which can lead to overheating and potential damage known as “hot spots.” This not only reduces overall power output but also shortens the lifespan of the PV system. The problem is particularly critical in urban environments where shading from adjacent structures is common [124,125].

Soiling is another environmental issue that severely impacts the performance of PV panels. Dust, dirt, snow, and other particles accumulating on the surface of the panels act as a barrier that blocks incoming sunlight, reducing energy production [126,127,128]. In desert locations or areas with high levels of pollution, the accumulation of soiling can occur quickly and affect large-scale systems. Frequent cleaning is required to mitigate this, which increases maintenance costs and presents logistical challenges for remote installations. Soiling also contributes to the mismatch problem, similar to shading, and can worsen over time if left unaddressed.

Another significant factor influencing PV performance is temperature. PV modules are sensitive to changes in temperature, and their efficiency decreases as temperatures rise. This is because higher temperatures increase the carrier recombination rate inside the solar cells, reducing the voltage and overall efficiency [123,129,130]. This can be shown in Fig. 12, which highlights how I-V curves are affected by different module temperatures. Although PV systems are typically installed in sunny locations where high temperatures are expected, excessive heat can still degrade performance and necessitate advanced cooling mechanisms or materials to maintain efficiency. Module temperature management is a crucial aspect of optimising performance, particularly in large-scale installations in hot climates.

Humidity and wind velocity also impact PV systems, though they are often considered secondary effects. High humidity can accelerate corrosion of electrical components, especially in coastal areas, which can reduce system reliability over time. While generally considered beneficial for cooling, wind velocity can create mechanical stress on mounting systems, particularly during storms or high-wind areas.

Manufacturing defects pose additional challenges, as imperfections during production can result in poor electrical characteristics and contribute to degradation over time. Over the system’s lifespan, these defects may cause a significant reduction in energy yield. Monitoring and quality control during the manufacturing process are essential to mitigate these issues, but they cannot be entirely avoided.

Integrating PV systems into the existing grid also presents technical challenges, particularly when balancing supply and demand. PV systems generate electricity intermittently, depending on sunlight availability, which can create instability in grid operations, especially with high levels of penetration. Large-scale PV systems require advanced inverters, energy storage solutions, and grid management technologies to mitigate issues such as voltage regulation, frequency fluctuation, and reverse power flow. Smaller, distributed PV systems, such as rooftop installations, introduce additional challenges in managing power quality and ensuring reliable connections to the grid.

Finally, PV systems are susceptible to various faults, including power fluctuations, low power factor, and inrush current, all of which degrade performance. Maintenance strategies are vital in addressing these issues, with different approaches including preventive, predictive, corrective, and urgent maintenance. Timely intervention is key to ensuring these faults do not significantly affect system performance or lead to costly repairs.

6.2. Challenge areas of CSP technology

While promising for renewable energy generation, Concentrated Solar Power (CSP) technology faces several significant challenges that can affect its feasibility and economic viability. One of the primary challenges is the reliance on solar irradiation, which is inherently intermittent. This creates critical design challenges and has severe economic implications. For instance, CSP systems often require supplementary conventional systems, like traditional reforming reactors, to ensure continuous operation during periods without sunlight, such as nighttime. This necessity increases system complexity and capital costs. The inherent intermittency makes it difficult to maintain a consistent energy supply for applications such as chemical processing and syngas generation, which cannot be shut down when sunlight is unavailable [131].

CSP plants are frequently located in arid and semi-arid regions,

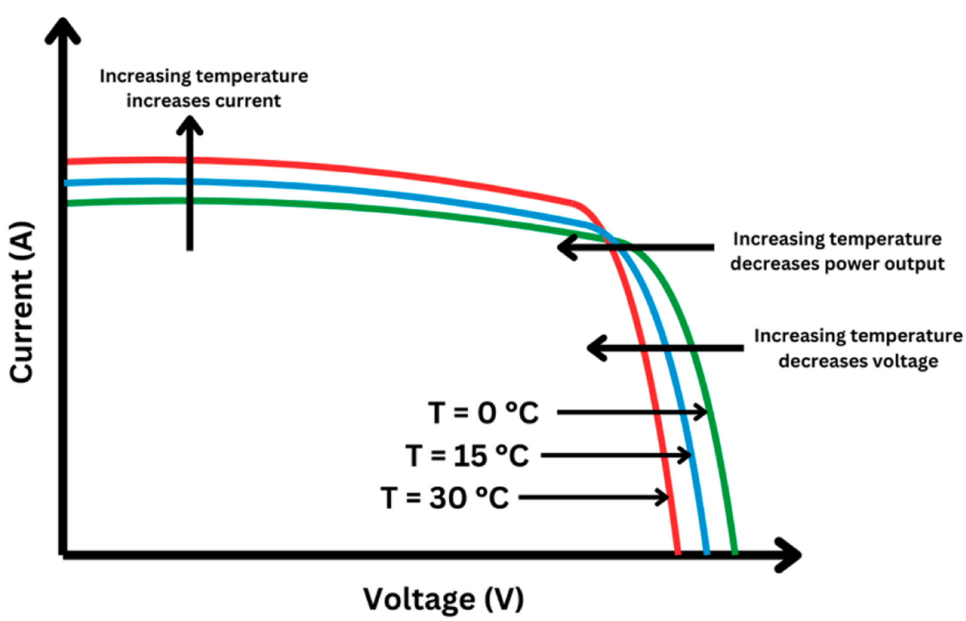

Fig. 12. I-V curve under different module temperatures.

where water scarcity poses a significant challenge. The water consumption for current CSP systems is estimated at 3 to 3.5 m^3/kWh, with the majority required for cooling towers and a smaller portion for mirror cleaning [132]. This high water requirement can be problematic in regions that are already water-stressed, necessitating the development of innovative cooling technologies such as dry cooling systems. While dry cooling can reduce water consumption by over 90 %, it typically requires a larger solar field and a higher initial investment. Additionally, some CSP technologies are not fully emission-free, necessitating further investments in carbon capture and storage technologies.

The technical challenges associated with CSP systems include high-temperature requirements for processes like solar thermolysis, which demands temperatures that CSP technologies may struggle to achieve. Moreover, separating hydrogen from the resulting hydrogen-oxygen mixture presents additional difficulties. CSP systems often provide lower efficiencies in solar thermal decomposition compared to traditional methane reforming. High gas flow rates and significant heat loss, along with issues related to recycling and material degradation, further complicate the operation of CSP technologies [133,134,135,136].

Economic considerations also play a crucial role in the viability of CSP systems. The cost of electricity generated from CSP technology is generally higher than that produced by utility-scale photovoltaic (PV) systems and other conventional energy technologies [136]. This cost disparity can limit the widespread adoption of CSP technologies, especially in competitive energy markets.

7. Conclusion

The future of solar technologies, particularly photovoltaic (PV) and concentrated solar power (CSP), is highly promising due to ongoing advancements in efficiency, cost reduction, and innovation in materials science. PV technology continues to dominate solar adoption, with recent breakthroughs in perovskite-silicon tandem cells and graphene applications leading to record power conversion efficiencies and enhanced stability. Simultaneously, CSP technology, with its inherent ability to provide energy storage, is evolving to address water scarcity and high capital costs through innovations in dry cooling systems and hybrid designs. Together, these advancements are expected to expand the role of solar energy in the global energy landscape, complementing each other to meet diverse energy demands.

The potential for solar energy to meet future global energy demands and mitigate environmental concerns is substantial, particularly with the rise of these technological innovations. Continued investment in both PV and CSP technologies, and their storage systems, will likely lead to greater market penetration and enable solar power to play a dominant role in the global energy mix. Addressing technical and non-technical barriers, such as regulatory frameworks and infrastructure inertia, will be key to realising the full potential of solar technologies in the coming decades.

CRediT authorship contribution statement

Moaz Osman: Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Imran Qureshi:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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